

REPORT 1352

EFFECT OF FUEL VARIABLES ON CARBON FORMATION IN TURBOJET-ENGINE COMBUSTORS¹

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SUMMARY

The effects of fuel properties and of a number of fuel additives on combustion-chamber carbon deposition and exhaust-gas smoke formation were investigated in a single tubular turbojet-engine combustor. Limited tests were conducted with a number of the fuels in several full-scale turbojet engines to verify single-combustor data.

At operating conditions simulating an engine with a compressor pressure ratio of 4 at an altitude of 20,000 feet and zero flight speed (condition A), carbon deposits and exhaust-gas smoke densities in the single combustor correlated with three empirical fuel factors: smoke-volatility index, smoke point, and NACA K factor (function of distillation characteristics and hydrogen-carbon ratio). The best correlations of deposits were obtained with smoke point and NACA K factor. At a condition of higher inlet air pressure and temperature simulating an engine with a compressor pressure ratio of 7 at sea level and a flight Mach number of 0.87 (condition B), the deposits and smoke densities did not satisfactorily correlate with any of the fuel factors considered. Further, only the data obtained at condition A correlated with limited full-scale-engine deposit data obtained with the same fuels. Deposits obtained at the higher pressure and temperature were considerably less uniform, and it is likely that large formations broke off the combustor walls during the test runs.

Carbon deposits in the single combustor were significantly reduced at condition A by the addition of organo-metallic compounds, commercial fuel additives that usually contained organo-metallic compounds, and oxygen-bearing compounds. Organo-metallic compounds, particularly those containing lead or iron, were most effective: dicyclopentadienyliron reduced deposits of a base fuel as much as 80 percent. The relative effectiveness of the additives depended on the properties of the base fuel. None of the additives significantly affected exhaust-gas smoke concentration.

INTRODUCTION

Carbon deposition in the combustors of turbojet engines constitutes an important operational problem, since such deposition can impair (1) combustion performance by affecting air and fuel distribution, (2) starting performance by fouling ignition electrodes, and (3) liner durability by causing liner cracking and warping. The presence of carbon as smoke in the exhaust gases of turbojet engines is less important; it does not, in general, impair engine performance, but it may be objectionable from a tactical or a nuisance standpoint. Deposits and smoke may be minimized by proper

combustor design and by selection of fuel properties. However, presently known remedies are not completely compatible with other combustor performance requirements and with fuel availability. Experiments aimed toward developing means of controlling carbon formation by limiting fuel characteristics and by using fuel additives are reported herein.

Many investigations have been conducted in both small-scale and full-scale combustors in an effort to develop a satisfactory means of predicting the carbon-forming propensity of turbojet fuels from results of simple laboratory fuels tests. Much of this work is summarized in reference 1. Approximate relations were found between deposits and several empirical factors derived from fuel properties. Smoke point, measured with a simple laboratory wick lamp, and NACA K factor, an empirical function of distillation characteristics and hydrogen-carbon ratio, gave the most accurate predictions of deposits for the data presented in reference 1. A "smoke-volatility index" (SVI) is currently included in military procurement specifications to limit carbon-deposition tendencies of jet fuels. This index, which is a function of the distillation characteristics and smoke point of the fuel, is easily determined and also has shown a satisfactory degree of correlation with deposits. The relation between smoke-volatility index and carbon formation in turbojet combustors with jet fuels varying widely in physical and chemical properties is examined herein. Also the relations obtained with the smoke-volatility index are compared with those obtained with smoke point and the NACA K factor.

Twenty fuels were tested in a single tubular turbojet combustor operated at conditions simulating an engine with a compressor pressure ratio of 4 at zero flight speed and an altitude of 20,000 feet. The fuels included a number of production JP-3 and JP-4 fuel samples and a number of fuels specially blended to provide wide variations in "fuel quality." In order to examine the effect of operating conditions on deposition, and hence on the general applicability of the fuel factors, six fuels were tested in the same combustor at conditions simulating operation in an engine with a compressor pressure ratio of 7 at a flight Mach number of 0.87 at sea level. The data obtained are generally limited to carbon deposition in the combustion chamber; however, some information is included on exhaust-gas smoke concentration with several of the fuels. Limited data obtained with some of the fuels in several full-scale engines are presented and compared with the single-combustor results.

¹ Supersedes recently declassified NACA Research Memorandums E52G11 by Edmund R. Jonash, Jerrold D. Wear, and William P. Cook; E52H21 by Edmund R. Jonash, Jerrold D. Wear, and William P. Cook; E53D15 by Jerrold D. Wear; E54H23 by Vincent F. Hlavjn and William P. Cook; E55D23 by Edmund R. Jonash, Helmut F. Butze, and William P. Cook; E55F30a by Edmund R. Jonash and William P. Cook; and E55J31 by Edmund R. Jonash, William P. Cook, and Jerrold D. Wear.

The use of a fuel additive capable of markedly reducing carbon deposition in combustion chambers would allow wider variations in jet fuel properties and hence greater fuel availability. A large variety of fuel additives has been suggested for preventing and removing carbon deposits in commercial furnaces and diesel engines. Several investigations in turbojet combustors have indicated at least moderate success with materials such as amyl nitrate, thiophene, and organo-metallic compounds (refs. 2 to 8). Carbon-deposition studies with some of the more promising fuel additives were conducted at the NACA Lewis laboratory, and the results of these studies are presented herein. The additives included four organo-metallic compounds, ten commercial fuel additives (most of which contained organo-metallic compounds), and nine oxygen-bearing compounds. The additives were blended, in most cases, with a No. 2 furnace oil. Limited data were also obtained with some of the additives blended with JP-3 and JP-4 fuels. Several additives were examined in more than one concentration to determine the effect of concentration. All experiments were conducted at the conditions simulating an engine with a pressure ratio of 4. The exhaust-gas smoke concentration was also measured.

FUELS AND ADDITIVES

The fuels used in this investigation are described in table I. They are designated by NACA-assigned numbers. Engine operating experience with fuels containing small concentrations of high-boiling aromatic hydrocarbons has shown that these components contribute markedly to carbon deposition.

TABLE I.—FUELS USED IN INVESTIGATION

Fuel (a)	Fuel type (b)	Description
50-264 51-353	JP-3 JP-3	"Low quality" 90 Weight-percent 50-264 plus 10 weight-percent triisopropylbenzene; high-boiling single-ring aromatic blend
52-50	JP-3	90 Weight-percent 50-264 plus 10 weight-percent of mixture of α - and β -monomethylnaphthalene; high-boiling dicyclic aromatic blend
52-32	JP-4	60 Weight-percent 50-264 plus 40 weight-percent triisopropylbenzene; high-boiling single-ring aromatic blend with H-C ratio very similar to 52-50
52-53 52-105	JP-4 JP-4	"High-quality" 90 Weight-percent 52-53 plus 10 weight-percent of mixture of α - and β -monomethylnaphthalene; high-boiling dicyclic aromatic blend; base fuel for additive tests
52-117	JP-4	"High quality"; blended from high-purity isoparaflinic hydrocarbons
52-118	JP-4	52-117 With low-boiling aromatic substituted for 15 percent isoparaflins of corresponding boiling range
52-119	JP-4	52-118 With polyethylbenzene substituted for isoparaflins of corresponding boiling range
52-120	JP-4	52-118 With methylnaphthalene substituted for isoparaflins of corresponding boiling range
52-166	JP-3	"Low quality"
52-28 52-30 52-74 54-108 54-109 54-110 54-111	JP-4 JP-3 JP-4 JP-4 JP-4 JP-4 JP-4	Used in single-combustor and full-scale-engine tests
52-288 53-49	JP-4 JP-4	
54-41	JP-4	
52-268 53-49	JP-4 JP-4	
54-41	JP-4	
49-162 49-224	JP-3 High-boiling aromatic	
53-193 55-89	Furnace oils	
		Base fuels for additive tests

* NACA designation.

b "Fuel type" refers only to volatility characteristics. Many of these fuels do not fall within MIL-F-5624B specifications in all respects.

The effects of high-boiling single-ring and dicyclic aromatic hydrocarbons on deposition were investigated with fuels 50-264, 51-353, 52-32, 52-50, 52-53, and 52-105 prepared at the NACA Lewis laboratory. The effects of low- and high-boiling single-ring aromatics and high-boiling dicyclic aromatics on deposition were investigated with fuels 52-117, 52-118, 52-119, and 52-120, which were distributed by the Coordinating Research Council as a part of a cooperative research program on carbon deposition. Fuels 54-108, 54-109, 54-110, and 54-111 were similarly distributed by the Coordinating Research Council to study the reliability of the smoke-volatility index as a measure of the carbon-forming propensity of JP-4 fuels. Most of the remaining fuels were JP-3 and JP-4 fuels of both high and low quality with respect to carbon-forming tendencies; many were obtained from refinery production batches. Fuels 49-162, 49-224, 53-193, and 55-89 were base fuels for most of the additive tests; 52-105 and 54-41 were also used as base fuels in some of these tests.

Fuel 52-30 (JP-3) is indicated herein as a fuel tested in both the single combustor and in a full-scale engine. Actually, the full-scale test was conducted with two different batches of JP-3 fuel. Fuel 52-30 was blended from these two batches, in the same proportions as used in the full-scale engine. The components of the blend had similar physical and chemical properties.

Analyses of the fuels examined are presented in table II. Smoke-volatility index (SVI) is defined as

$$SVI = \text{Smoke point} + 0.42(\text{vol.-percent fuel boiling under } 400^\circ \text{ F})$$

Military fuel procurement specification MIL-F-5624B, which contains an SVI limitation, requires that smoke point be determined by method 2107 of specification VV-L-791. Most of the fuels listed in table II were tested before the acceptance of this method. The smoke points reported for these fuels were measured with the modified Davis factor lamp described in reference 9. The two test methods agree reasonably well, and no distinction is made between them in this report.

The NACA K factor (table II) is a function of the volatility and hydrogen-carbon ratio of the fuel:

$$K = (t + 600)(0.7) \frac{(H/C) - 0.207}{(H/C) - 0.259}$$

where t is the volumetric average boiling temperature ($^\circ\text{F}$), and H/C is the hydrogen-carbon ratio. Values of the K factor were estimated from an enlargement of figure 3 of reference 1.

Although the mechanism by which additives might reduce carbon formation is not understood, it has been suggested that the presence of an oxygen-bearing compound in the area where carbon is formed may result in oxidation of the carbon. Some success has been obtained in experiments with alkyl nitrates, particularly amyl nitrate (ref. 5). Other means of providing an oxygen-bearing compound would be fuel-soluble organo-metallic compounds, which, when burned, will produce a metallic oxide. The additives listed in table

TABLE II.—FUEL PROPERTIES

MIL-F-562AB		NACA fuel																				55-59			
Grade JP-3	Grade JP-4	40-162	40-224	50-204	51-353	52-28	52-30	52-32	52-33	53-53	52-70	52-105	52-117	52-118	52-119	52-120	52-106	52-288	53-49	53-193	54-41	54-103	54-109	54-110	54-111
ASTM distillation Dist-52, °F:																									
Percent:																									
Initial point...	109	327	100	124	137	119	128	114	136	142	134	135	144	143	139	105	139	180	356	140	120	136	170	140	378
6	135	352	120	170	178	167	180	167	183	201	183	200	207	208	202	142	254	205	406	198	171	176	220	192	408
10	153	357	162	205	194	196	224	205	200	220	204	233	229	233	175	175	253	247	430	235	210	217	240	224	428
20	210	364	224	260	217	244	304	263	225	244	231	278	257	266	261	243	291	310	460	278	273	267	263	207	448
30	270	372	268	305	239	272	350	283	244	293	253	322	284	286	291	289	311	348	482	312	324	304	298	286	468
40	323	383	301	322	256	295	397	322	293	283	272	360	318	328	320	324	370	500	550	330	350	329	312	285	486
50	368	393	330	358	275	310	423	350	278	304	261	390	353	354	379	351	353	395	510	360	372	348	334	301	500
60	398	406	368	401	299	337	434	401	301	324	314	409	393	382	404	389	347	418	530	393	396	397	385	341	516
70	432	421	413	428	317	392	442	425	321	348	343	440	418	405	420	419	393	455	548	434	399	385	378	381	532
80	462	444	444	445	347	401	449	461	347	381	381	455	440	437	445	440	382	462	594	477	410	403	400	407	544
90	500	482	477	469	400	460	468	474	400	438	431	485	479	473	467	470	413	474	580	521	426	423	438	446	580
(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)	(max.)
End point...	584	583	512	512	480	517	500	510	498	494	488	530	533	533	532	515	480	510	622	572	475	470	490	514	613
Residue, %	1.5	1.4	1.2	1.3	1.2	1.4	1.1	1.2	1.2	1.2	0.0	1.7	1.7	1.5	1.1	1.3	-----	-----	1.5	1.2	1.0	1.2	1.5	1.5	2.0
Loss, %	1.5	1.0	1.8	1.3	1.0	1.1	0.4	0.8	0.7	0.8	0.3	0.3	0.4	0.3	0.4	0.8	-----	-----	0	0.8	1.0	0.8	0	0	0
Freezing point, °F	-70	<-70	<-70	-----	-----	-----	-----	-----	-----	<-70	-----	<-70	<-70	<-70	<-70	<-70	<-70	<-70	<-15	<-70	<-76	<-70	<-70	<-70	2
Rold vapor pressure, lb/sq in.	5.0-7.0	4.5	6.0	-----	2.8	5.4	2.0	-----	2.0	2.3	-----	2.1	1.9	1.9	2.0	0.1	2.7	2.3	-----	2.3	2.0	2.4	1.7	2.4	-----
Aromatics, % by volume	25.0	31	20	-----	10	-----	-----	-----	10.7	24	17	3	19	27	26	24	10	14	30	20.5	20.9	28.1	16.3	22.1	22.4
Bromine number	-----	12	8.0	-----	-----	-----	-----	-----	-----	-----	-----	2.5	2.9	2.4	4.0	10.0	-----	2.0	6	7.0	-----	-----	-----	5.4	-----
Accelerated gum, mg/100 ml	14	10	12	-----	-----	-----	-----	-----	-----	3	-----	21	12	22	28	51	-----	12	01	80	85.7	34.7	6.1	15.3	37
Existent gum, mg/100 ml	7	8	9	-----	-----	-----	-----	-----	-----	1	-----	4	5	5	11	18	-----	3	25	51	4.1	1.0	2.3	5.0	3
Hydrogen-carbon ra- tio	-----	0.160	0.153	0.162	0.171	0.108	0.149	0.148	0.170	0.160	0.160	0.181	0.168	0.103	0.160	0.162	0.168	0.101	0.147	0.149	0.162	0.164	0.164	0.163	0.163
Heat of combustion, ° Btu/lb	18,400	18,475	18,400	18,400	18,725	18,675	18,275	18,360	18,700	18,475	18,575	19,080	18,825	18,700	18,050	18,425	18,075	18,625	18,400	18,300	18,400	18,450	18,000	18,475	18,475
Aniline-gravity prod- uct	6250	-----	5110	4441	7400	6945	3138	3942	7335	5133	6069	10,518	8353	7212	6844	4703	6950	5547	4415	4100	4355	4888	6383	6455	6054
Specific gravity, 60°/ 60° F	-----	0.801	0.791	0.804	0.760	0.771	0.822	0.810	0.757	0.787	0.779	0.762	0.708	0.778	0.791	0.800	0.770	0.811	0.801	0.825	0.803	0.783	0.785	0.794	0.849
Gravity, °API	45-55	-----	47.3	44.5	55.8	52.1	40.0	41.8	55.4	48.2	50.2	50.7	52.7	50.4	47.3	45.4	50.8	43.0	32.9	40.0	44.8	47.0	45.8	46.7	35.1
Aniline point, °F	-----	-----	108.8	99.8	133.7	133.3	77.3	94.3	132.4	106.5	120.7	135.5	138.5	143.1	144.7	103.0	130.8	129.0	134.2	104.0	97.2	104.0	130.8	110.8	144.0
Smoke-volatility Index	54.0	-----	46.5	38.9	78	66	28.2	30.9	72.3	51	59.3	83.2	54.4	49.5	42.0	42.3	93.3	43	13.5	40.1	43.8	49.5	55.0	40.4	15.1
Smoke point, mm	-----	-----	417.2	413.0	440.0	432.3	411.0	411.9	434.5	410.5	424.0	445.1	428.1	421.0	418.0	415.0	432.0	421.0	413.7	414.2	417.0	423.0	426.0	417.1	13.8
NACA K factor	-----	346	331	341	262	277	393	363	258	310	300	227	285	304	332	358	278	321	415	337	341	330	205	318	393

* Determined by combustion furnace.

b Method not listed.

c Estimated from aniline-gravity constant.

d Determined by modified Davis factor lamp (ref. 9).

e Determined by method 2107 of specification VV-1-701.

f Ref. 1.

TABLE III.—COMPOSITIONS OF ADDITIVE BLENDS

Additive	Composition	Additive concentrations		NACA base fuel
		By volume, Gal additive	By weight, per- cent by weight of blend	
		1000 Gal fuel		
Materials of known composition				
<i>n</i> -Propyl nitrate..... Amyl nitrate..... Isobutyl nitrate..... <i>n</i> -Butyl nitrate.....	----- ----- ----- Technical grade.....	4.12, 8.27 4.32, 8.68 4.52, 9.08 30.9	0.5, 1.0 0.5, 1.0 0.5, 1.0 3.7	53-193 53-193 53-193 55-89
Amyl nitrite.....	29.4 Weight-percent isoamyl nitrite, 70.6 weight-percent <i>n</i> -amyl nitrite.	28.1	2.76	55-89
2-Nitropropane..... Nitrobenzol.....	Technical grade..... Technical grade.....	30.9 30.9	3.5 4.2	55-89 55-89
<i>tert</i> -Butyl hydro- peroxide.	60 Weight-percent solution in <i>tert</i> - butyl alcohol.	30.9	3.1	55-89
Diethyl ether.....	Pure grade.....	30.9	2.5	55-89
Dicyclopenta- dienyliron.	30 Weight-percent iron.	-----	0.005, 0.01, 0.03, 0.04, 0.05	53-193
Cadmium naph- thenate.	10 Weight-percent cadmium.	-----	0.2	53-193
Lead naphthe- nate.	37 Weight-percent lead.	-----	0.0025, 0.005 0.01, 0.10	52-105
		-----	0.0025, 0.005	49-224
Tetraethyl lead..	64 Weight-percent lead.	-----	0.00145, 0.00292	49-224
Commercial additives ¹				
A.....	Lead, copper.....	1.0 0.50, 1.0 1.0	0.106 0.0531, 0.1062 0.1082	53-193 53-193 54-41
B.....	Copper, calcium.....	1.0	0.0982	53-193
C.....	Chromium.....	0.91	0.1090	53-193
D.....	Calcium, sodium.....	0.25 .25	0.0299 .0299	53-193 54-41
E.....	Cobalt.....	1.06	0.1096	53-193
F.....	Lead, cobalt.....	1.0 -----	0.0970 0.05, 0.10, 0.21	53-193 49-162
G.....	Calcium.....	0.50, 1.0	0.0488, 0.0975	53-193
H.....	Lead.....	2.50	0.283	53-193
I.....	Lead.....	2.50	0.286	53-193
J.....	Lead.....	2.50	0.259	53-193

¹ Composition is result of qualitative spectroscopic analyses.

III that are of known composition were chosen to represent a variety of oxygen-bearing organic materials, including four alkyl nitrates, an alkyl nitrite, two nitro-compounds, a peroxide, an ether, and a variety of organo-metallic compounds of iron, cadmium, or lead. Two different compounds of lead were tested, lead naphthenate and tetraethyl lead. The commercial additives listed in table III varied in their intended application. They included diesel fuel additives, gasoline additives, and oil furnace cleaners. None were developed specifically for turbojet combustor application, but all were intended to remove or retard carbon and soot formation resulting from the combustion of low-grade fuels. In most cases these additives contained only a small concentration of an active ingredient in a fuel-soluble carrier. They were examined spectroscopically to determine their principal elemental constituents.

The additive concentrations investigated (table III) were based on published and unpublished test data obtained from other laboratories and on recommendations by the manufacturers of the additives. In several cases a number of

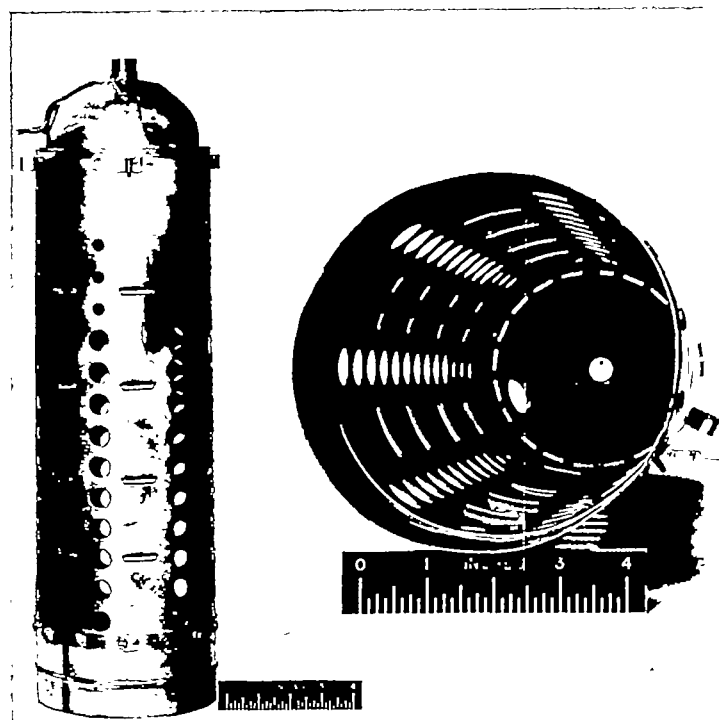


FIGURE 1.—Liner and dome of J33 single combustor used in carbon-deposition investigation.


additive concentrations were investigated; in many cases the quantity of additive available limited the number of tests conducted. Since the experiments were made over a period of years, several different base fuels were employed. The base fuels were chosen for their high carbon-forming propensity.

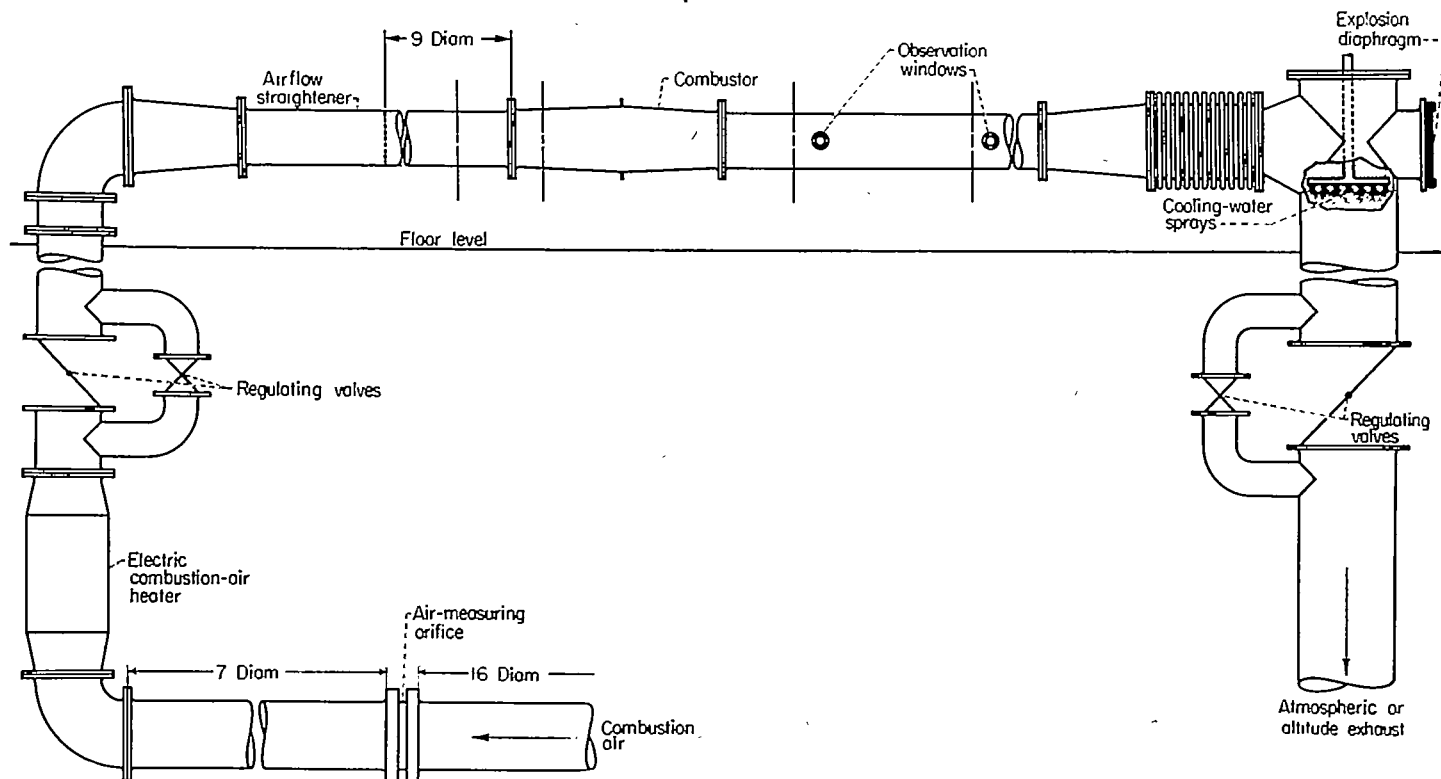
APPARATUS AND PROCEDURE

SINGLE COMBUSTORS

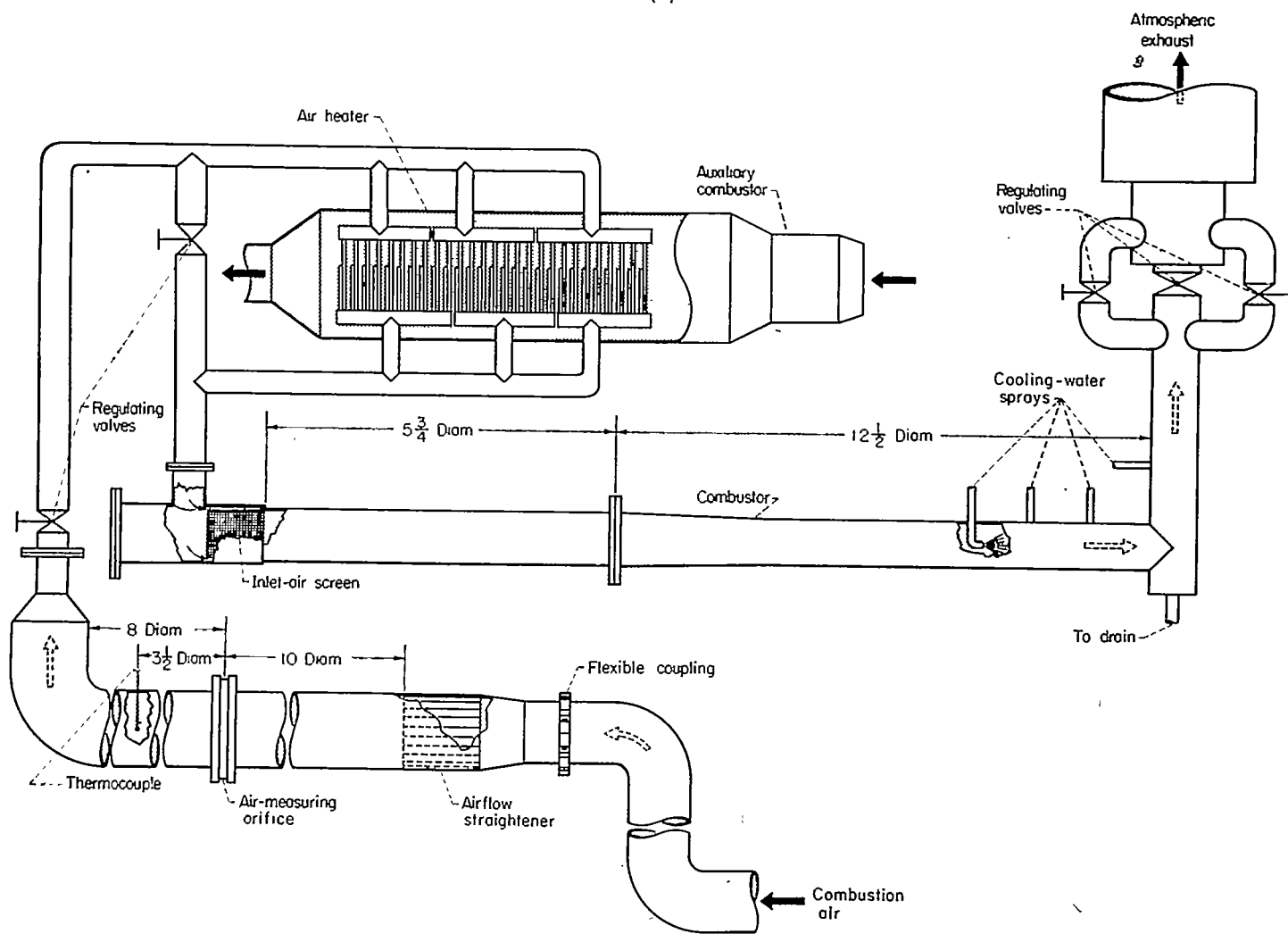
Installation.—The single-combustor tests were conducted with the J33 liner and dome assembly shown in figure 1. The liner and dome from a production engine were welded together to assure consistent alinement of parts in each test. The facility in figure 2(a) was used for tests at low inlet air pressure and temperature, and that in figure 2(b) for the higher inlet air pressure and temperature. The combustor liner and dome were installed in a housing similar to the J33 combustor housing, except that circular inlet and exhaust transition sections were used. Airflow rate and air pressure in the combustor were controlled by remotely operated valves in the combustor inlet and outlet ducting. Water-spray nozzles in the exhaust ducts cooled the gases prior to their passage through the exhaust control valves.

The desired combustor-inlet air temperature was obtained by using either electric preheaters (fig. 2(a)) or a gasoline-fired heat exchanger (fig. 2(b)). The gasoline-fired heat exchanger consisted of a series of coiled Inconel tubes, connected in parallel, through which the high-pressure air flowed. The tubes were heated externally, in crossflow, by combustion gases from an auxiliary turbojet combustor. Airflow and fuel-flow rates to the combustor were measured by means of square-edged orifice plates (installed according to ASME specifications) and calibrated rotameters, respectively.

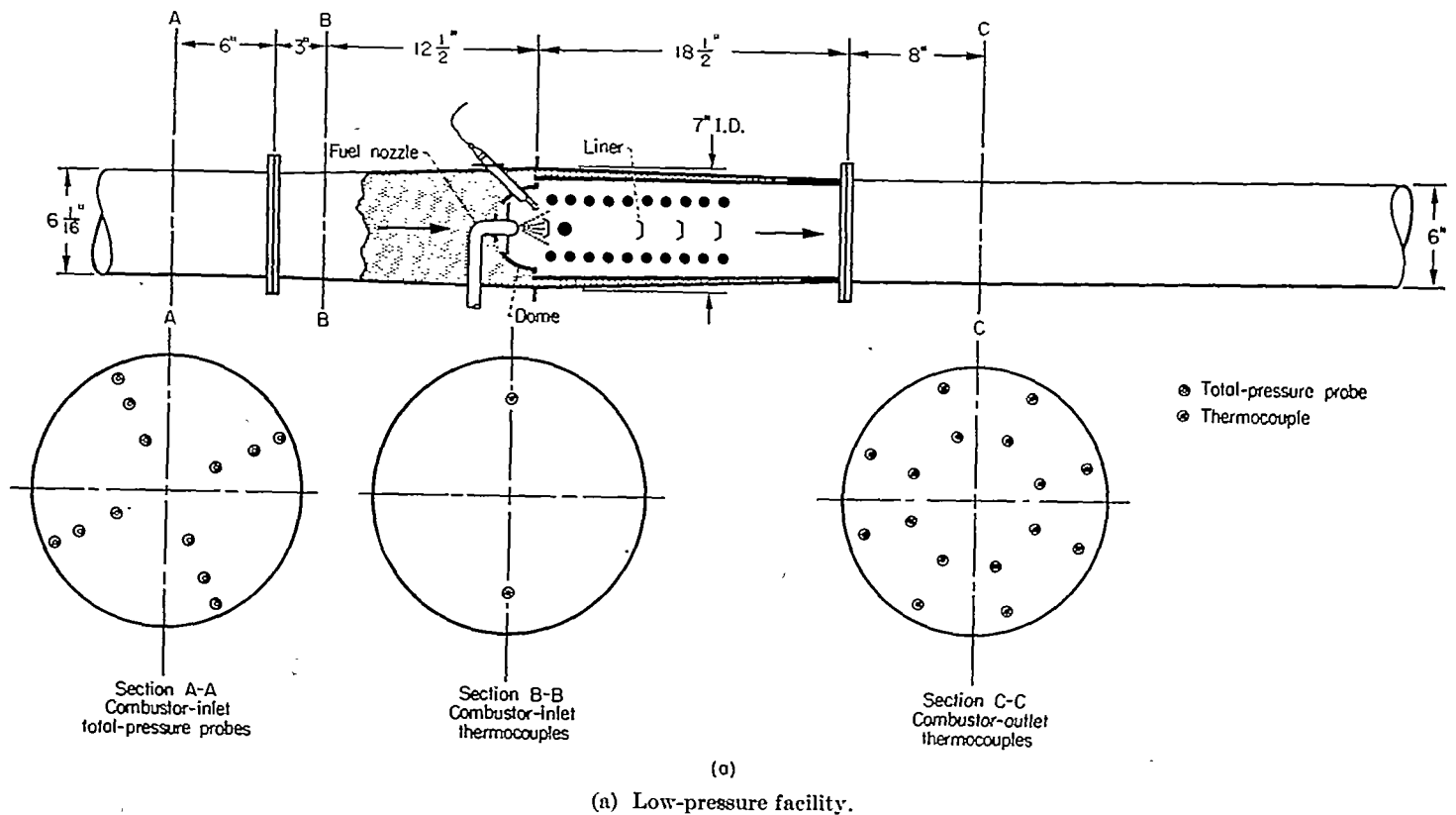
(a) Low-pressure facility. (b) High-pressure facility. 
FIGURE 2.—Single-combustor installation and auxiliary equipment.



(a)



(b)



Combustor-inlet total-pressure probes,
plane x-x, and thermocouples, plane y-y

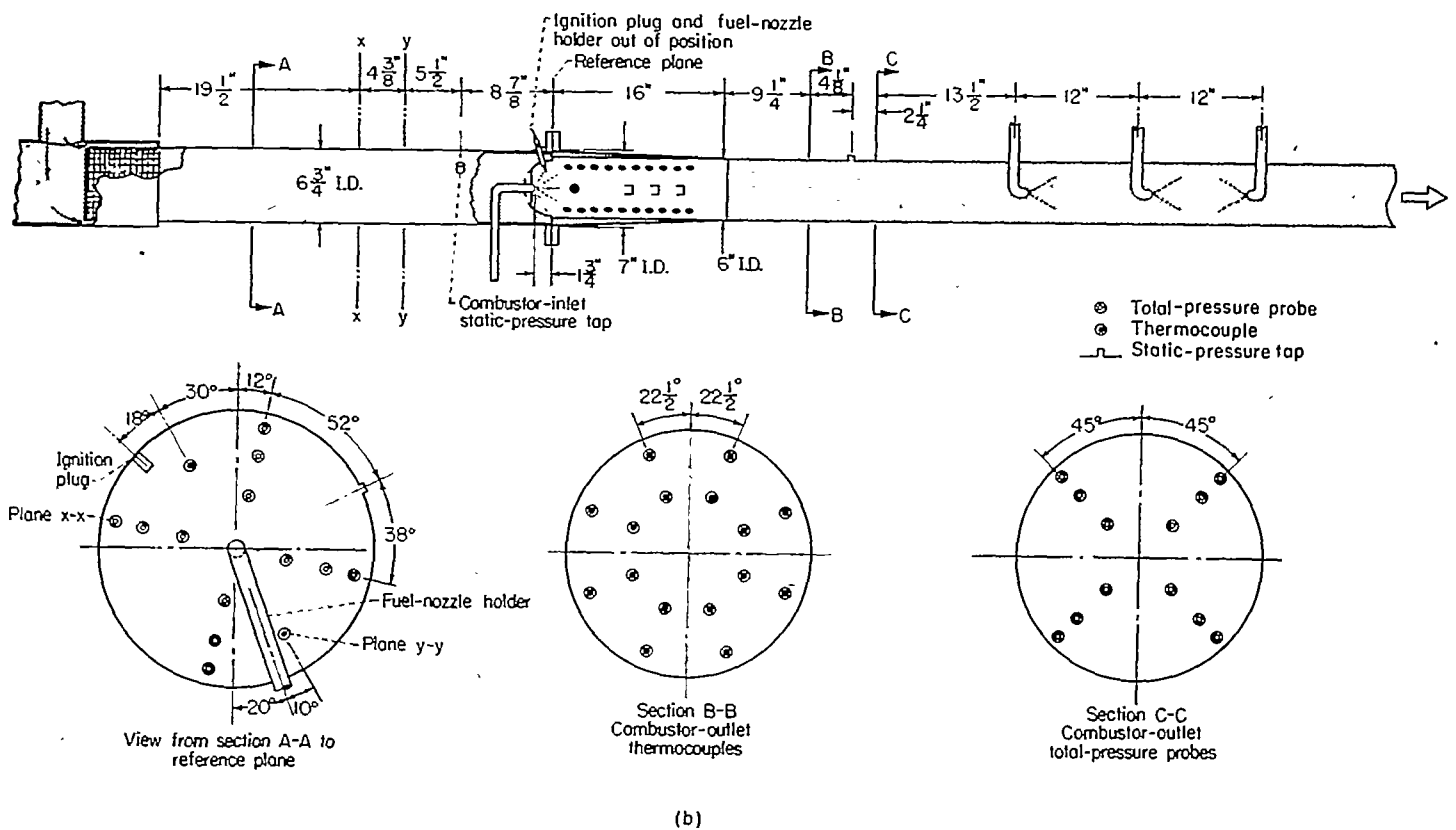
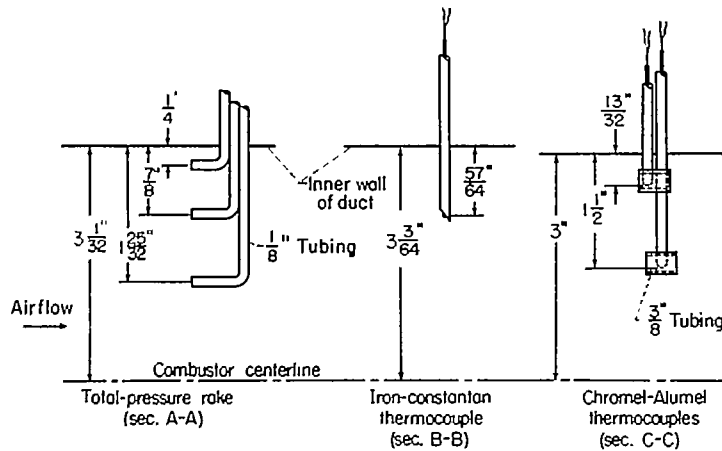


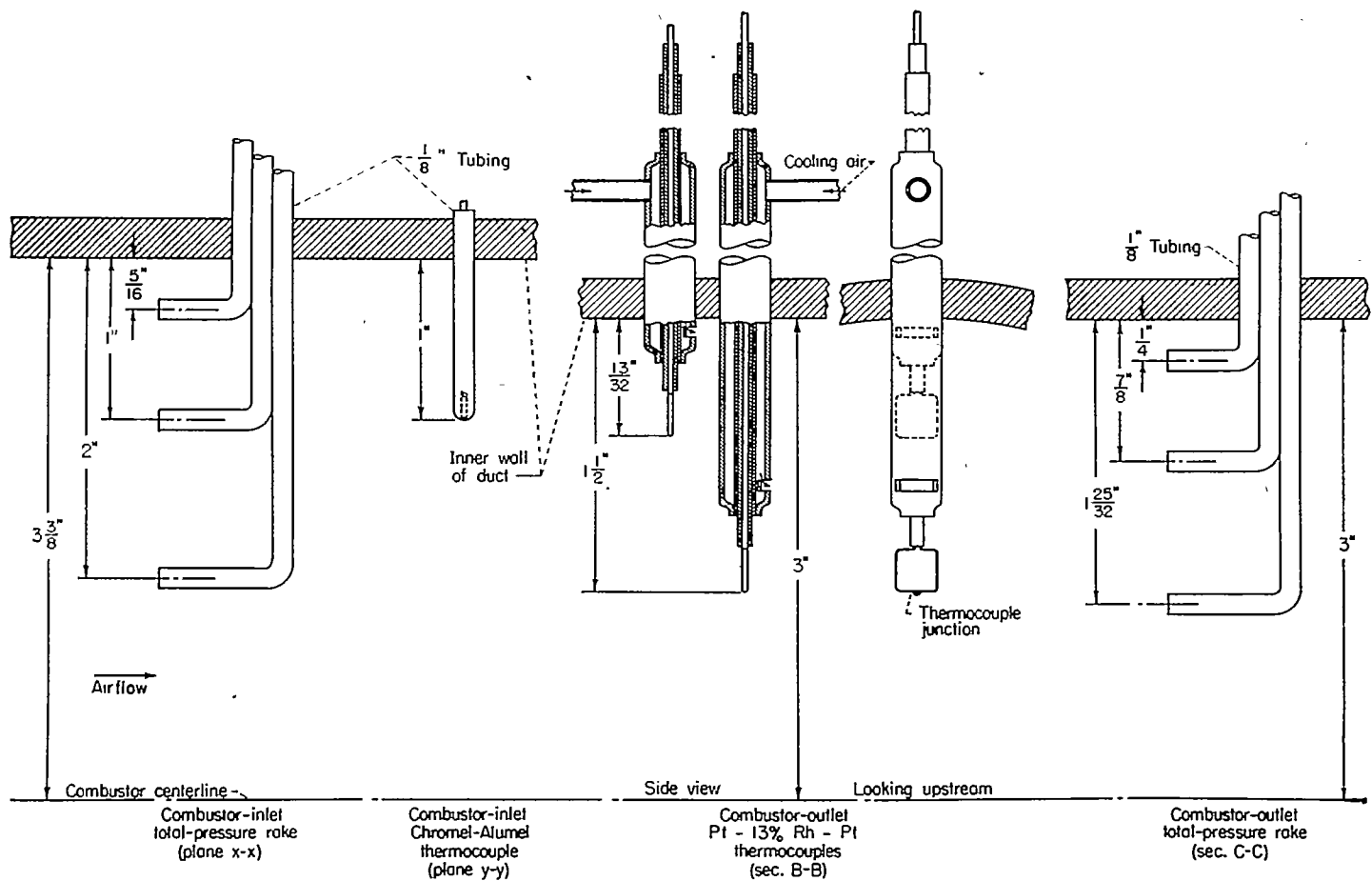
FIGURE 3.—Cross section of single-combustor installation showing auxiliary ducting and location of temperature- and pressure-measuring instruments in instrumentation planes.

Combustor temperature and pressure instrumentation.—Diagrammatic cross sections of the combustor and its auxiliary ducting and the position of instrumentation planes in the test installation are shown in figure 3. Thermocouples



(a) Low-pressure facility.

and total-pressure tubes in each instrumentation plane were located at centers of equal areas. Construction details of the temperature- and pressure-measuring instruments are shown in figure 4. In the low-pressure installation iron-constantan thermocouples were used to measure combustor-inlet air temperature (sec. B-B, fig. 3(a)), and Chromel-Alumel thermocouples to measure combustor-outlet gas temperature (sec. C-C, fig. 3(a)). The pressure and temperature data were obtained by means of manometers and automatic-balancing potentiometers, respectively. In the high-pressure facility the inlet air and exhaust gas temperatures were measured by Chromel-Alumel thermocouples (plane y-y, fig. 3(b)), and by platinum-13-percent-rhodium-platinum thermocouples (sec. B-B, fig. 3(b)), respectively. The supports for the platinum-rhodium-platinum thermocouples were made of brass and were cooled by a stream of high-pressure air bled from the combustion-air supply upstream of the orifice. Inlet air and exhaust gas total pressures were measured by the probes shown in figure 4(b) connected to strain-gage pressure transducers. All combustor pressures and temperatures were indicated on automatic-balancing potentiometers.



(b) High-pressure facility.

FIGURE 4.—Construction details of temperature- and pressure-measuring instruments.

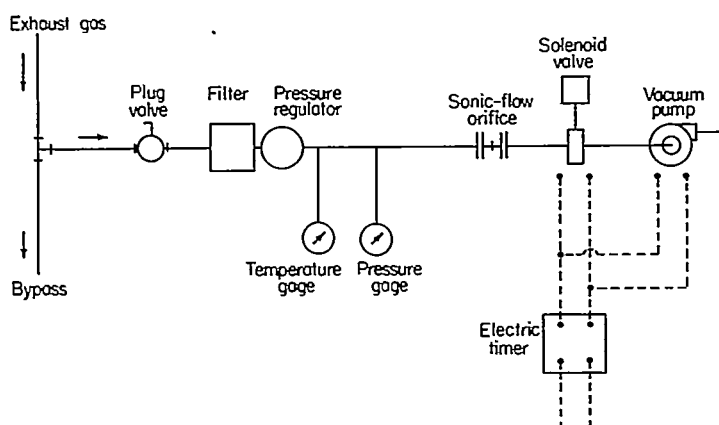


FIGURE 5.—Diagram of smoke meter.

Smoke measurements.—In the low-pressure facility, exhaust gas samples were withdrawn through a single total-head probe centrally located in the exhaust duct. In the high-pressure facility the samples were obtained from a three-point total-head probe located in the exhaust duct. The apparatus used to determine the relative quantity of smoke in the exhaust gases was a modification of a commercially available smoke tester (shown diagrammatically in fig. 5). The meter consisted essentially of an air-cooled filter press containing a paper filter disk, and an automatic metering system. The gas sample was metered through a sonic-flow orifice; the flow duration was controlled by a solenoid valve actuated by an electric timer. A pressure-regulating valve maintained constant upstream orifice pressure. Location of the filter upstream of the control equipment eliminated the possibility of depositing soot on the control valves and orifice. The relative amounts of exhaust-gas smoke, reported as "smoke density," were measured by a transmission densitometer. The values reported represent the difference in optical density between the smoke-covered and the clean filters.

Experimental procedure.—The single-combustor tests were conducted at the following combustor operating conditions:

	Condition	
	A	B
Inlet air total pressure, lb/sq in. abs.	23.5	141.0
Inlet air temperature, °F	271	640
Airflow rate, lb/sec.	2.87	12.0
Exhaust gas temperature, °F	1100	1800
Combustor reference velocity, ft/sec.	110	180
Approximate fuel-air ratio	0.012	0.018
Run time, hr	4	1.5
Approximate simulated full-scale-engine conditions:		
Compressor pressure ratio	4	7
Engine rpm, percent rated	90	100
Altitude, ft	20,000	0
Flight Mach number	0	0.87

Combustor reference velocity is based on the maximum cross-sectional area of the combustor, the weight flow of air, and the density of the air at combustor-inlet conditions. The conditions were chosen to represent two widely different

test conditions; no attempt was made to investigate the effect of any individual operating parameter. Twenty fuels were tested at condition A, and six JP-4 fuels were tested at condition B. The run time was decreased to 1.5 hours at condition B because of limited supplies of several of the fuels and because of the limited life of the combustor liner at the higher pressure and temperature. All additive tests were conducted at condition A.

For carbon-deposition measurements, the combustor liner and dome assembly, including the ignition plug, was cleaned with mechanical rotating brushes and weighed on a torsion-type balance before the test run. After the prescribed period of operation the assembly was reweighed; the difference in weight represented the amount of carbon deposition reported herein. Generally, at least one check test was conducted. The exhaust-gas smoke density was measured at intervals during each run. The values of smoke density reported herein are averages of the several individual measurements made during each test run.

After each test with a fuel-additive blend, the fuel system was drained and purged with the base fuel to remove any residual additive. One or more check runs with the base fuel were made between tests with each of the additives to determine the effectiveness of the purge and the reproducibility of the base-fuel deposits.

FULL-SCALE ENGINES

Three full-scale turbojet engines were run at various engine conditions in the carbon-deposition investigation.

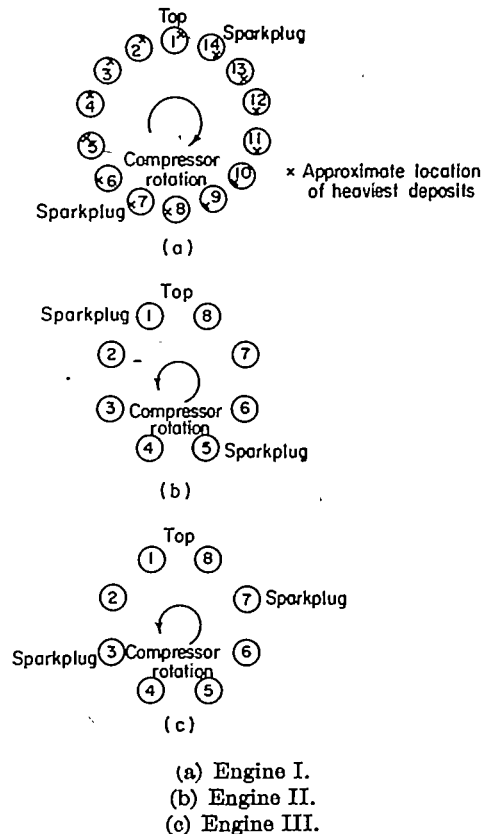


FIGURE 6.—Diagrams showing relative locations of combustors in full-scale engines (looking downstream).

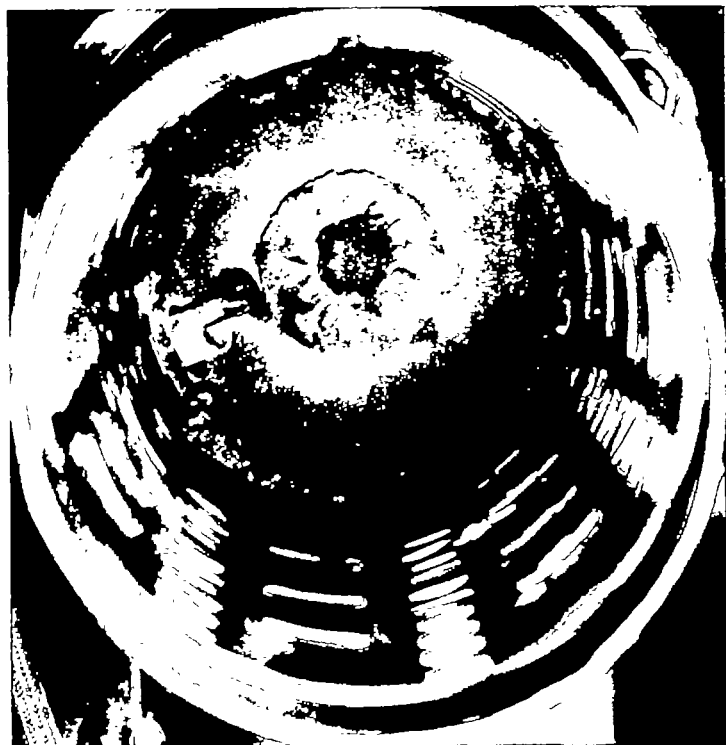


FIGURE 7.—Carbon deposits in J33 single-combustor liner after 4-hour run with fuel 49-224.

Engine I.—Engine I had a centrifugal-flow compressor with a pressure ratio of 4 and 14 individual tubular combustors. The combustor numbers, sparkplug locations, and direction of compressor rotation are shown schematically in figure 6(a). The engine was operated at sea level at zero flight speed on a cyclic operating schedule. The operating cycle consisted in approximately 5 minutes at idle engine speed (4000 rpm) followed by 15 minutes at takeoff speed (11,500 rpm). The idle time included the time for acceleration and deceleration. There was no regularly scheduled shutdown period. The performance of the engine was investigated at 6000 rpm before each day of operation to ascertain constancy of performance. The intended run time for each test was 50 hours. Both new and used combustor liners and used domes were cleaned, if necessary, but not weighed before any one test. After the completion of the test, the liners and domes were weighed, cleaned with wire brushes, and reweighed. The difference in weight was considered the weight of the carbon deposited.

Engine II.—Engine II had an axial-flow compressor with a pressure ratio of 5 and eight individual tubular combustors (fig. 6(b)). The engine was operated at sea-level static conditions for a total time of 25 hours. This time was divided into seven 3-hour periods followed by a 4-hour period. At the beginning and end of each period, the engine was operated for 5 minutes at rated conditions (7600 rpm); during the rest of each period, it was operated at 90-percent rated speed. Following each period of operation, the engine was shut down for approximately 2 hours. The new combustor liners used for the investigation were weighed before and after 25 hours of operation, and the increase in weight was considered as the weight of the carbon deposited.

Engine III.—Engine III had an axial-flow compressor with a pressure ratio of 5.2 and eight individual tubular combustors (fig. 6(c)). This engine was operated at sea-level static conditions for a total time of 37 hours and 47 minutes. The maximum running time for any one day was about 1½ hours, which included running at engine speeds from 3000 to 7950 rpm. About 75 percent of the total operating time was at 7950 (rated) rpm, and the other 25 percent at engine speeds varying between 3000 and 7950 rpm. The complete test covered a time period of about 1½ months. Combustor liners, which had been previously used, were cleaned with wire brushes and then weighed before and after the complete test. The increase in weight was considered as the weight of the carbon deposited.

RESULTS

EFFECT OF FUEL PROPERTIES ON CARBON DEPOSITS IN SINGLE COMBUSTORS

A photograph of carbon deposits obtained in the J33 combustor during a 4-hour test run with fuel 49-224 is presented in figure 7. The deposits, which were concentrated in the upstream end of the liner around the fuel-injection nozzle and the sparkplug, weighed about 34 grams. Carbon-deposition data obtained in this type combustor with 21 fuels are presented in table IV. At the lower inlet air pressure and temperature (condition A), average deviations in individual test results from average test results varied from 1 to 16 percent. At condition B the average deviations were greater, varying from 8 to 30 percent.

TABLE IV.—SINGLE-COMBUSTOR DEPOSITS WITH FUELS VARYING IN PHYSICAL AND CHEMICAL PROPERTIES

NAACA fuel	Carbon deposit, g					Average variation, % (a)	
	Run						Average
	1	2	3	4	5		
Condition A							
50-264	9.2	12.8	11.6	10.4	-----	11.0	11
51-353	13.5	15.4	14.3	-----	-----	14.4	5
52-28	-----	-----	-----	-----	-----	^b 2.5	-----
52-30	-----	-----	-----	-----	-----	^c 3.7	-----
52-32	16.1	17.9	17.5	-----	-----	17.2	4
52-50	14.4	13.9	14.0	-----	-----	14.1	1
52-53	2.2	2.4	-----	-----	-----	2.3	4
52-76	-----	-----	-----	-----	-----	^c 7.4	-----
52-105	6.4	6.8	-----	-----	-----	6.6	3
52-117	1.1	1.2	1.3	-----	-----	1.2	5
52-118	4.8	5.4	4.9	-----	-----	5.0	5
52-119	6.8	6.8	6.1	-----	-----	6.6	5
52-120	11.4	12.0	13.1	-----	-----	12.2	5
52-166	^b 7.2	^b 7.7	^b 7.1	-----	-----	^b 7.3	3
53-49	-----	-----	-----	-----	-----	^b 6.9	-----
54-41	21.4	23.3	24.0	28.0	26.8	24.7	9
54-108	16.2	17.0	16.3	-----	-----	16.5	2
54-109	13.9	15.3	15.5	-----	-----	14.9	5
54-110	8.1	6.4	6.4	-----	-----	7.0	11
54-111	^b 8.9	^b 6.0	^b 9.0	-----	-----	^b 8.0	16
Condition B							
52-288	3.3	2.4	-----	-----	-----	2.9	16
54-41	7.0	9.2	6.3	-----	-----	7.5	15
54-108	5.2	2.8	-----	-----	-----	4.0	30
54-109	11.0	9.0	-----	-----	-----	10.0	10
54-110	6.3	5.4	-----	-----	-----	5.9	8
54-111	2.3	3.6	-----	-----	-----	2.9	21

^a Arithmetical average percent variation of individual carbon-deposition value from arithmetical average deposition.

^b Gray deposits.

^c Average of two or more tests.

Gray deposits were obtained with fuels 52-28, 52-166, 53-49, and 54-111. As will be noted in a later section of this report, similar-colored deposits were observed in tests with fuels containing small amounts of lead or cadmium. Spectrographic analysis of the deposits with fuel 54-111 at condition A indicated lead, which is assumed to have been present in the fuel as a contaminant. The deposits with this fuel at condition B showed no evidence of lead. It is very possible that the lead was present in the fuel as tetraethyl lead, the antiknock additive used in aviation gasoline. The high inlet air temperature at condition B may have vaporized this volatile compound so rapidly that no significant quantity reached the carbon-forming areas of the liner walls. Another possible explanation for the inconsistency is that the fuel was received in fourteen 55-gallon drums, only a part of which may have been contaminated.

Average deposits obtained at conditions A and B are plotted against smoke-volatility index, smoke point, and NACA K factor in figure 8. At condition A the deposits generally increased with decreasing smoke-volatility index or smoke point and with increasing K factor. The solid symbols of figure 8 denote deposits that showed evidence of metal contamination. These data points were not considered in the fairing of the correlation curves. Tailed symbols in figure 8 denote deposit data obtained in earlier phases of the investigation. At condition B the general trends are the same as those at condition A; however, the deviations from a mean correlation curve are much greater.

EFFECT OF FUEL PROPERTIES ON CARBON DEPOSITS IN FULL-SCALE ENGINES

Engine I.—The carbon deposits obtained with three test fuels in engine I are presented in table V(a). The values represent results of a single test with each fuel. Locations of the heaviest deposits are as shown in figure 6(a). No relation between the relative quantities of carbon and the circumferential position of the combustor is evident. Emission spectra of gray powder deposits obtained from the downstream end of liners after the test with fuel 52-28 indicated that these deposits contained a large amount of lead. Similar deposits were noted with this fuel in the single-combustor tests (table IV).

Fuel-nozzle filter plugging during the first test with fuel 52-76 limited the fuel flow to the engine to such an extent that the desired engine speed could not be maintained; the test was terminated after 37 hours and 54 minutes. This

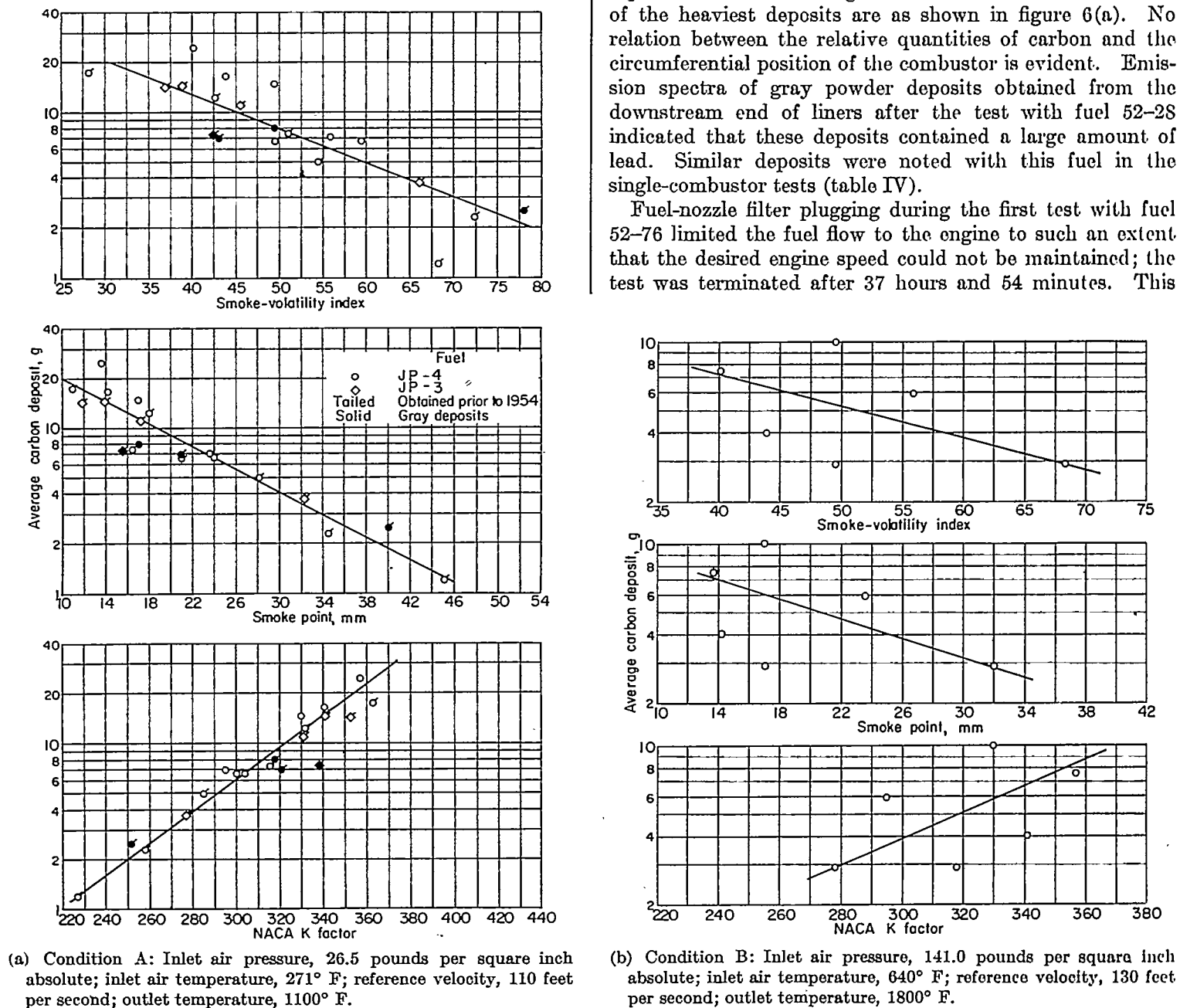


FIGURE 8.—Relation between average carbon deposits in single tubular combustor and empirical fuel factors.

run is not included in the analysis of data but is shown in table V(a) only to indicate, approximately, the effect of time and the reproducibility of the amount of carbon obtained from a single fuel. In a second test with fuel 52-76 the desired number of running hours was obtained, although some filter plugging did occur. A considerable amount of carbon remained on the ignition plugs after fuel 52-76 was used.

Engine II.—The carbon deposits obtained in engine II with a minimum-quality JP-3 fuel (50-264) are presented in table V(b). The values represent results of a single test. Carbon deposits were found in the dome end of the combustor and on the fuel nozzle. There was some evidence of greater

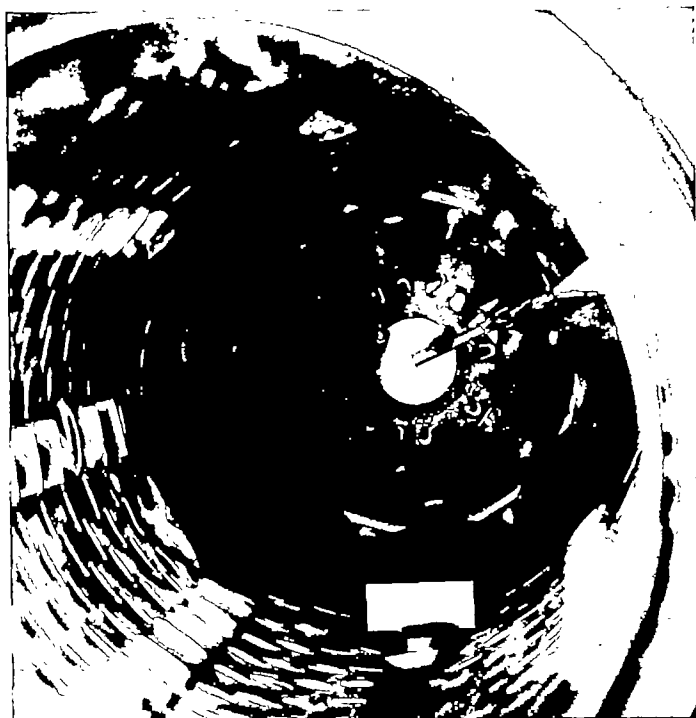


FIGURE 9.—Carbon deposits obtained in combustor 7 of full-scale engine III with fuel 52-76.

deposition in combustion chambers located at the bottom of the engine. A much larger amount of soot was found in the exhaust muffler than had been obtained from previous tests of this duration with a production JP-3 fuel.

Engine III.—Carbon deposits obtained in engine III with a minimum-quality JP-4 fuel (52-76) are shown in table V(c). The values represent results of a single test. The large deposit weight obtained in combustor 7 (fig. 6(c)) was caused by a large deposit on one of the sparkplugs, as shown in figure 9. Abnormally large deposits in combustors using the type of sparkplug shown in figure 9 have been obtained previously. Several of the liners were severely warped after the test and had to be replaced.

During the test with this fuel, the exhaust cooling water draining from the exhaust muffler was black. Inspection of the inside of the muffler showed large quantities of soot; one total-pressure rake was plugged with soot. This amount of exhaust soot was much greater than that normally encountered with production JP-4 fuel.

TABLE V.—FULL-SCALE-ENGINE DEPOSITS WITH VARIOUS FUELS

(a) Three fuels in engine I.

Combustor	Fuel 52-30		Fuel 52-28		Fuel 52-76			
	Run time							
	49 hr 20 min				37 hr 54 min		50 hr 30 min	
	Carbon deposition, g							
	Liner	Dome	Liner *	Dome	Liner	Dome	Liner *	Dome
1.....	4.2	22.7	4.8	13.3	8.9	19.3	7.9	19.2
2.....	6.2	16.1	4.6	7.8	7.7	12.7	.6	1.5
3.....	7.7	10.0	5.9	7.9	4.9	11.2	9.8	19.1
4.....	7.4	12.9	4.8	5.1	.7	1.8	5.8	13.4
5.....	7.3	20.5	7.2	14.1	8.6	13.0	7.8	16.3
6.....	7.0	13.7	3.4	8.2	14.1	15.3	18.0	22.3
7.....	8.0	17.8	4.8	13.1	7.4	17.6	7.7	12.4
8.....	3.7	25.3	6.0	6.3	8.4	21.0	9.1	11.9
9.....	6.3	15.4	4.4	11.9	7.2	10.5	10.1	15.2
10.....	5.7	25.0	5.6	7.7	8.0	11.9	7.3	12.3
11.....	3.9	10.4	4.0	9.4	7.3	18.2	11.5	15.6
12.....	4.4	13.1	5.0	6.8	6.3	15.1	14.0	24.3
13.....	5.4	17.1	5.7	7.5	9.3	18.0	10.2	11.0
14.....	5.8	11.4	7.0	16.5	9.0	21.7	12.4	14.0
Total.....	83.0	231.4	73.2	135.6	107.8	203.3	132.2	207.5
Average per liner or dome..	5.9	16.5	5.2	9.7	b 8.2	b 15.5	c 10.1	c 15.9
Average per combustor....	22.4		14.9		b 23.7		c 26.0	

* New liners.

^b Values of combustor 4 not used in averages, because partly plugged fuel-nozzle filter resulted in a lean mixture and consequently a decrease in carbon deposits.

^c Values of combustor 2 not used in averages.

(b) Fuel 50-264 in engine II. Run time, 25 hours.

Combustor	Carbon, g
1.....	9.4
2.....	7.9
3.....	8.5
4.....	12.6
5.....	10.7
6.....	9.1
7.....	5.0
8.....	9.2
Total.....	72.4
Average.....	9.1

(c) Fuel 52-76 in engine III. Run time, 37 hours 47 minutes.

Combustor	Carbon, g
1.....	5.2
2.....	5.7
3.....	10.0
4.....	8.6
5.....	4.6
6.....	3.8
7.....	42.1
8.....	2.2
Total.....	82.2
Average.....	10.3

TABLE VI.—SINGLE-COMBUSTOR EXHAUST-GAS SMOKE DATA

NACA fuel.....	54-108		54-109		54-110		54-111	
Condition.....	A	B	A	B	A	B	A	B
Smoke density..	0.14	0.23	0.18	0.31	0.07	0.13	0.13	0.12
	.10	.37	.14	.28	.06	.18	.13	.10
	.14	.29	.12	.41	.09	.....	.13	.15
	.18	.....	.13	.46	.05	.....	.11	.16
	.21	.....	.19	.....	.03	.....	.09	.....
	.16	.....	.20	.....	.03	.....	.11	.....
	.18	.....	.20	.....	.04	.....	.13	.....
	.13	.....	.14	.....	.05	.....	.07	.....
	.10	.....	.....	.....	.....	.....	.....	.....

Average smoke density.....	0.15	0.31	0.16	0.37	0.05	0.16	0.11	0.13
Average deviation, %.....	20	12	19	19	30	16	16	17

EFFECT OF FUEL PROPERTIES ON SMOKE FORMATION

Exhaust-gas smoke data were obtained only in the single combustor with fuels 54-108, 54-109, 54-110, and 54-111 (table VI). In most cases two or three determinations were made during each carbon-deposit test run. Average percentage deviations varied from 12 to 30 percent. Because of inaccuracies in the smoke measurement technique, the

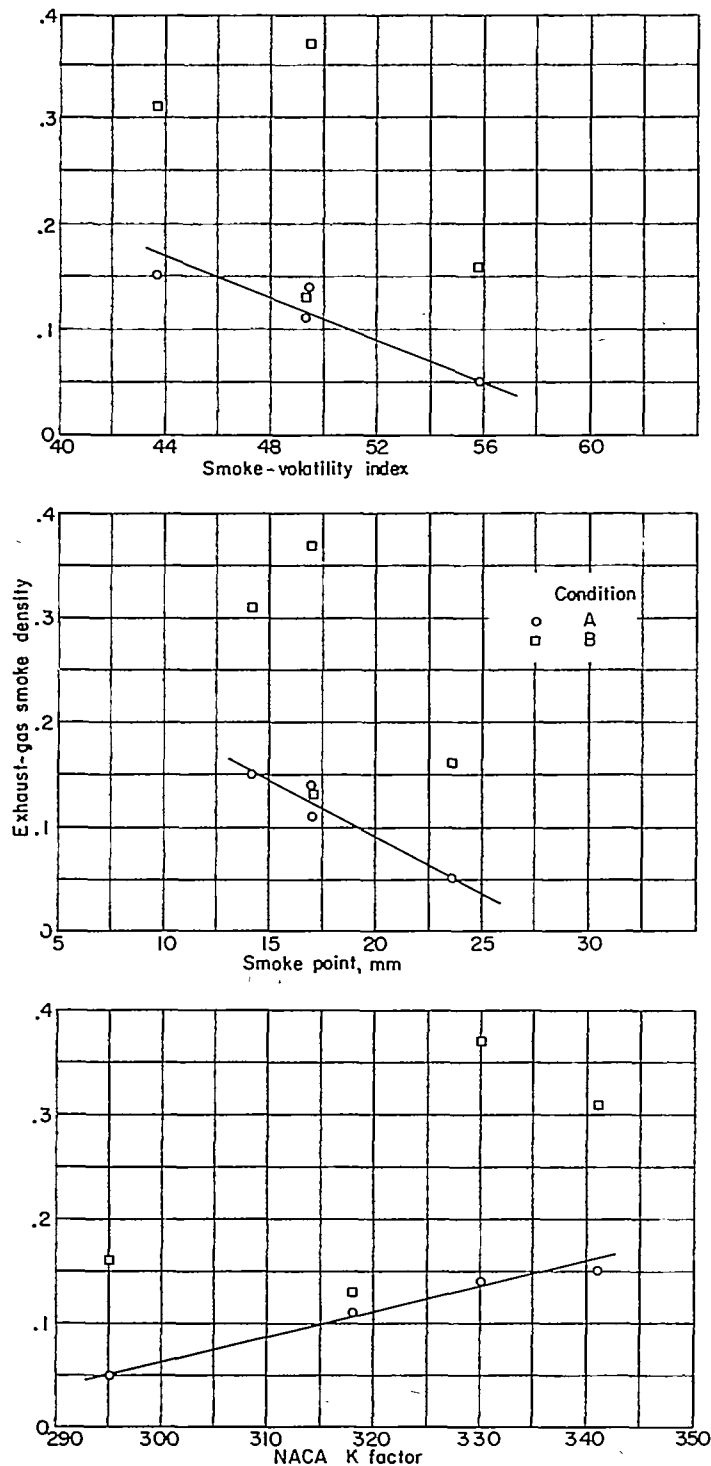


FIGURE 10.—Relation between exhaust-gas smoke density obtained with JP-4 fuels and empirical fuel factors.

larger percentage deviations generally occurred at lower values of smoke density. Average smoke densities are plotted in figure 10 against smoke-volatility index, smoke point, and NACA K factor. At both conditions exhaust-gas smoke density decreased with increasing smoke-volatility index or smoke point and with decreasing K factor. A reasonable correlation was obtained only at condition A, however; and only the data for this test condition were used to fair the curves in figure 10.

EFFECT OF ADDITIVES ON CARBON DEPOSITION AND EXHAUST-GAS SMOKE

The effect of a number of fuel additives on carbon deposition and exhaust-gas smoke concentration was investigated in the single turbojet combustor at condition A. The tests were conducted over a considerable period of time with a number of different base fuels. In some cases the base fuel was changed to determine the effect of some additives on the carbon-forming properties of different fuel compositions. In other cases, the supply of base fuel was depleted and new supplies varied in composition.

The results obtained in tests with 23 different additives are presented in table VII. With base fuels 49-162, 49-224, 52-105, 54-41, and 55-89, representing a wide variety of fuel properties, reproducibility was considered satisfactory; the average deviations in individual test runs from the average deposit obtained in all runs with the particular base fuel ranged from 2 to 21 percent. Base fuel 53-193 was used during several periods of the investigation. During any one period, reproducibility with this fuel was also satisfactory, with average deviations from 1 percent (run series 15) to 14 percent (run series 28 through 43). However, the average base-fuel deposit obtained in each of the several periods of operation differed considerably: The average deposit in run series 15 was 20.5 grams; in run series 28 through 43 it was 28.3 grams; and in run series 44 through 53, 35.6 grams. The large difference may be partly attributed to aging, which would increase the gum content of the fuel and may affect deposits (ref. 10).

Multiple additive test runs were conducted where sufficient quantities of the additive were available. For the multiple

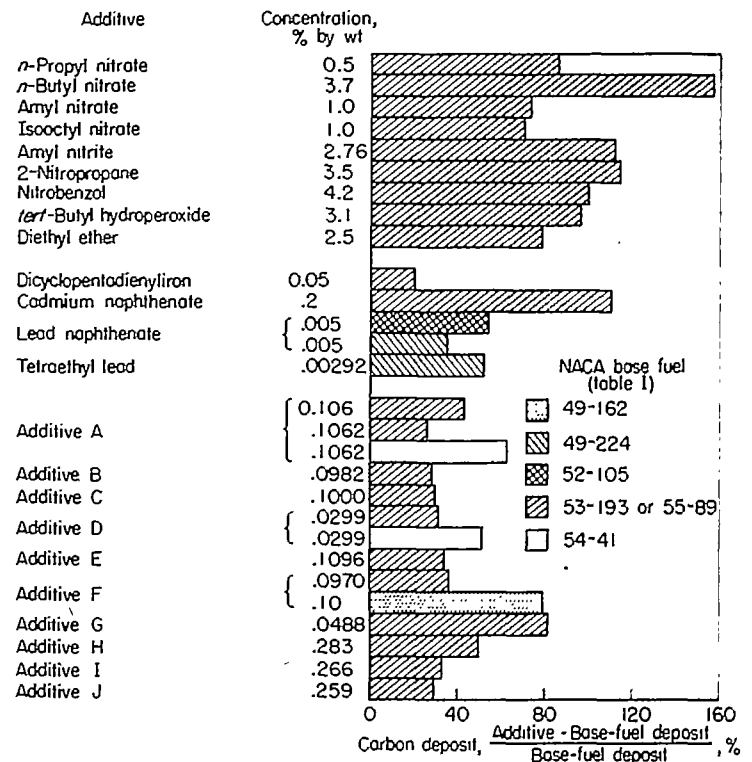


FIGURE 11.—Relative effectiveness of 23 additives in reducing turbojet combustion-chamber carbon deposits.

TABLE VII.—CARBON-DEPOSIT AND EXHAUST-GAS SMOKE DATA WITH FUEL ADDITIVES

Run series	Base fuel	Additive (table III)	Additive concentration, % by weight	Carbon deposit, g							Av. variation, % (a)	Change from base-fuel deposit, % (b)	Exhaust-gas smoke rating					
				Run						Av.								
				1	2	3	4	5	6									
1	49-162	None	-----	13.9	15.0	13.5	13.8	-----	-----	14.1	3.6	-----	---	---	---	---	---	---
2		F	0.05	13.4	-----	-----	-----	-----	-----	13.4	-----	-5.0	---	---	---	---	---	---
3			.10	10.7	11.8	10.9	-----	-----	-----	11.1	3.9	-21.3	---	---	---	---	---	---
4			.21	13.3	-----	-----	-----	-----	-----	13.3	-----	-5.7	---	---	---	---	---	---
5	52-105	None	-----	6.4	6.8	6.5	6.4	-----	-----	6.5	1.9	-----	---	---	---	---	---	---
6		Lead naphthenate	0.0025	3.9	-----	-----	-----	-----	-----	3.9	-----	-40.0	---	---	---	---	---	---
7			.005	3.5	3.5	-----	-----	-----	-----	3.5	0	-46.2	---	---	---	---	---	---
8			.01	3.6	-----	-----	-----	-----	-----	3.6	-----	-44.6	---	---	---	---	---	---
9			.10	14.9	13.2	-----	-----	-----	-----	14.1	6.1	116.9	---	---	---	---	---	---
10	49-224	None	-----	17.9	22.4	31.1	30.6	-----	-----	25.5	21.0	-----	---	---	---	---	---	---
11		Lead naphthenate	0.0025	13.0	-----	-----	-----	-----	-----	13.0	-----	-49.0	---	---	---	---	---	---
12			.005	8.8	-----	-----	-----	-----	-----	8.8	-----	-65.5	---	---	---	---	---	---
13		Tetraethyl lead	0.00145	19.6	-----	-----	-----	-----	-----	19.6	-----	-23.1	---	---	---	---	---	---
14	.00292		13.3	-----	-----	-----	-----	-----	13.3	-----	-47.8	---	---	---	---	---	---	
15	53-193	None	-----	20.7	20.6	20.1	-----	-----	-----	20.5	1.2	-----	0.40	0.38	0.45	---	---	---
16		A	0.1062	4.9	5.6	-----	-----	-----	-----	5.3	6.6	-74.1	0.37	0.47	---	---	---	---
17			.0531	5.9	6.2	-----	-----	-----	-----	6.1	2.6	-70.2	.41	---	---	---	---	---
18		B C D E F	0.0982	5.8	-----	-----	-----	-----	-----	5.8	-----	-71.7	0.40	---	---	---	---	---
19			.1000	6.5	5.9	-----	-----	-----	-----	6.2	4.8	-69.8	.48	0.41	---	---	---	---
20			.0299	6.5	6.3	-----	-----	-----	-----	6.4	1.6	-63.8	.42	.49	---	---	---	---
21			.1096	7.3	6.5	-----	-----	-----	-----	6.9	5.8	-66.3	.36	.42	---	---	---	---
22			.0970	8.2	6.5	-----	-----	-----	-----	7.4	11.5	-63.9	.43	.38	---	---	---	---
23		G	0.0975	15.6	18.0	19.8	-----	-----	-----	17.8	8.2	-13.2	0.42	0.38	0.32	---	---	---
24			.0488	16.6	-----	-----	-----	-----	-----	16.6	-----	-19.0	.49	---	---	---	---	---
25	54-41	None	-----	21.4	23.3	24.0	-----	-----	-----	22.9	4.2	-----	0.21	0.14	0.24	---	---	---
26		A D	0.1062	13.1	15.1	-----	-----	-----	-----	14.1	7.1	-38.4	0.18	0.20	---	---	---	---
27			.0299	12.2	11.0	-----	-----	-----	-----	11.6	5.2	-49.3	.15	.24	---	---	---	---
28	53-193	None	-----	28.7	31.7	32.4	-----	-----	-----	30.9	4.9	-----	0.18	0.22	0.24	---	---	---
29		Cadmium naphthenate	0.2	33.0	29.0	-----	-----	-----	-----	31.0	6.5	9.5	0.24	0.20	---	---	---	---
30		None	-----	33.4	-----	-----	-----	-----	-----	33.4	-----	-----	0.15	-----	---	---	---	---
31		A II	0.106	12.1	-----	-----	-----	-----	-----	12.1	-----	-57.2	0.26	---	---	---	---	---
32			.283	14.6	13.3	-----	-----	-----	-----	14.0	4.7	-50.5	.17	0.14	---	---	---	---
33		None	-----	23.2	18.0	-----	-----	-----	-----	20.6	12.6	-----	0.24	0.27	---	---	---	---
34		I J	0.266	8.9	9.1	-----	-----	-----	-----	9.0	1.1	-63.2	0.17	0.26	---	---	---	---
35			.259	9.8	6.8	-----	-----	-----	-----	8.3	18.1	-70.7	.20	.23	---	---	---	---
36		None	-----	24.9	34.6	23.7	-----	-----	-----	27.7	16.5	-----	0.27	0.17	0.22	---	---	---
37			-----	29.0	28.8	-----	-----	-----	-----	28.9	.3	-----	.36	.48	---	---	---	---
38	Dicyclopentadienyliron	0.005	14.0	12.3	-----	-----	-----	-----	13.2	6.5	-53.4	0.52	0.46	---	---	---	---	
39		.03	8.1	6.4	-----	-----	-----	-----	7.3	11.7	-74.2	.54	.57	---	---	---	---	
40		.01	12.1	11.6	-----	-----	-----	-----	11.9	2.1	-53.0	.45	.50	---	---	---	---	
41		.04	6.8	-----	-----	-----	-----	-----	6.8	-----	-76.0	.46	---	---	---	---	---	
42		.05	5.7	-----	-----	-----	-----	-----	5.7	-----	-79.9	.41	---	---	---	---	---	
43	None	-----	31.4	-----	-----	-----	-----	-----	31.4	-----	-----	0.34	-----	---	---	---	---	
44	53-193	n-Propyl nitrate	0.5	25.9	32.4	29.4	33.5	-----	-----	30.3	8.8	-14.9	0.26	0.19	0.23	0.21	---	---
45		-----	1.0	34.4	35.3	-----	-----	-----	-----	34.9	1.3	-2.0	.23	.19	---	---	---	---
46		None	-----	32.4	28.8	32.1	33.7	-----	-----	31.8	4.6	-----	0.22	0.20	0.27	0.24	---	---
47		Isooctyl nitrate	0.5	30.7	37.3	28.5	-----	-----	-----	32.2	10.7	-9.6	0.26	0.24	0.23	---	---	---
48			1.0	30.8	21.2	25.2	22.1	-----	-----	24.8	12.8	-30.3	.21	.17	.25	0.20	---	---
49		None	-----	36.3	37.7	41.1	31.4	35.5	36.5	36.4	5.6	-----	0.22	0.30	0.26	0.34	0.34	0.33
50		Amyl nitrate	0.5	24.3	25.7	29.9	-----	-----	-----	26.6	8.1	-25.3	0.24	0.18	0.26	---	---	---
51		None	-----	43.0	29.8	42.7	35.6	-----	-----	37.8	13.5	-----	0.19	0.27	0.21	0.24	---	---
52		Amyl nitrate	1.0	26.8	30.0	21.1	-----	-----	-----	26.0	12.4	-27.0	0.25	0.27	0.21	---	---	---
53		None	-----	38.1	-----	-----	-----	-----	-----	38.1	-----	-----	0.16	-----	---	---	---	---
54	55-89	None	-----	20.6	20.4	21.0	-----	-----	-----	20.7	1.1	-----	0.23	0.36	0.41	---	---	---
55		2-Nitropropane	3.5	22.5	-----	-----	-----	-----	-----	22.5	-----	13.6	0.38	-----	---	---	---	---
56		None	-----	21.1	-----	-----	-----	-----	-----	21.1	-----	-----	0.37	-----	---	---	---	---
57		n-Butyl nitrate	3.7	31.0	-----	-----	-----	-----	-----	31.0	-----	56.6	0.36	-----	---	---	---	---
58		None	-----	18.3	-----	-----	-----	-----	-----	18.3	-----	-----	0.34	-----	---	---	---	---
59		tert-Butyl hydroperoxide	3.1	19.0	-----	-----	-----	-----	-----	19.0	-----	-4.0	0.46	-----	---	---	---	---
60		None	-----	18.6	16.1	17.5	-----	-----	-----	17.4	5.0	-----	0.41	0.35	0.41	---	---	---
61		Nitrobenzol	4.2	19.7	-----	-----	-----	-----	-----	19.7	-----	-0.5	0.50	-----	---	---	---	---
62		None	-----	23.2	19.1	-----	-----	-----	-----	21.2	9.7	-----	0.41	0.50	---	---	---	---
63		Amyl nitrite	2.76	22.1	-----	-----	-----	-----	-----	22.1	-----	11.6	0.40	-----	---	---	---	---
64		None	-----	21.4	20.4	-----	-----	-----	-----	20.9	2.4	-----	0.47	0.36	---	---	---	---
65		Diethyl ether	2.5	15.5	-----	-----	-----	-----	-----	15.5	-----	-21.7	0.45	-----	---	---	---	---
66		None	-----	19.3	-----	-----	-----	-----	-----	19.3	-----	-----	0.43	-----	---	---	---	---

a Average variation of individual carbon-deposit values from average deposit value.

b Average deposit minus over-all average base-fuel deposit

Over-all average base-fuel deposit

tests the mean deviation of deposits in individual test runs from the average deposit values varied from 0 to 18 percent. The percent changes in deposit from the base-fuel deposit are based upon average deposit values obtained with the base fuel during the period of testing with the particular additive. For test run series 28 through 43 the average base-fuel deposit value of 28.3 (obtained from runs 28, 30, 33, 36, 37, and 43) was used for additive data obtained in intervening test runs. Similarly, for runs 44 through 53 an average base-fuel deposit value of 35.6, obtained from run series 46, 49, 51, and 53, was used.

The relative effectiveness of the additives in reducing carbon deposits is compared in figure 11. Average carbon deposits, in percentage of base-fuel deposits, are shown only for the additive concentrations that gave the largest reductions in deposit. In general, the oxygenated compounds (alkylated nitrates, amyl nitrite, nitropropane, nitrobenzol, *tert*-butyl hydroperoxide, and diethyl ether) were considerably less effective than the organo-metallic compounds and the commercial additives, which were also primarily organo-metallic. The most effective oxygenated compound, isooctyl nitrate, reduced base-fuel deposits almost 30 percent, while the most effective organo-metallic compound, dicyclopentadienyliron, reduced base-fuel deposits about 80 percent. Additive A, the most effective of the commercial additives, reduced base-fuel deposits 74 percent. A quali-

tative spectroscopic analysis of additive A showed that it contained lead and copper (table III).

A comparison of results obtained with a number of additives (A, D, and lead naphthenate) that were tested in more than one base fuel indicates that the relative effectiveness of an additive varied markedly with the base fuel. For example, additive A in No. 2 furnace oil (53-193) reduced deposits 74 percent; the same concentration of additive A in the same furnace oil at a much later date (aged fuel) reduced deposits 57 percent; and the same additive in a high-carbon-forming JP-4 fuel (54-41) reduced deposits 38 percent.

The effect of additive concentration on carbon deposits was determined with nine of the additives. Figure 12 shows that the effect of additive concentration on deposits was not consistent. For some additives (dicyclopentadienyliron and lead naphthenate), small concentrations produced the large reductions in deposits. A high concentration of lead naphthenate in fuel 52-105 produced deposits greater than those obtained with the base fuel alone.

Deposits obtained with additive blends containing lead or cadmium were colored gray or yellow-gray in some areas of the combustor liner. The deposits obtained with dicyclopentadienyliron were reddish. These colorations indicate the presence of metal and metal oxides. The deposits were not chemically analyzed.

Exhaust-gas smoke data were obtained with many of the base fuels and additive-base-fuel blends; these data are presented in table VII. Large variations in smoke ratings were observed with the base fuels, and the smoke ratings of the additive blends were generally within the ranges obtained with the base fuels. Hence, no effect of the additives on smoke concentration is apparent.

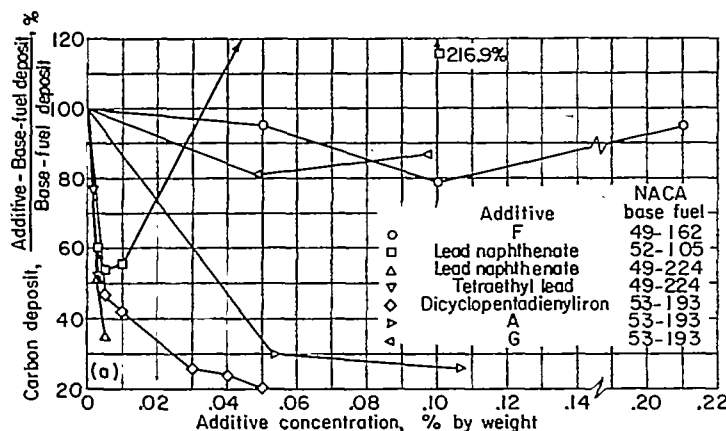
DISCUSSION

EMPIRICAL RELATIONS BETWEEN CARBON DEPOSITS AND FUEL PROPERTIES

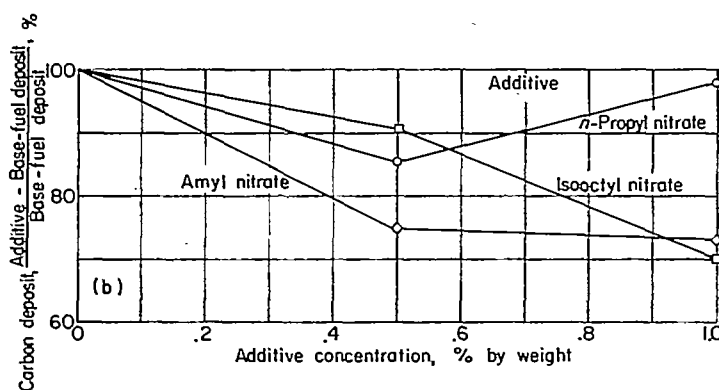
Single-combustor carbon deposits obtained at inlet air temperature and pressure simulating operation of an engine with a compressor pressure ratio of 4 at a 20,000-foot altitude (condition A) correlated reasonably well with any of three empirical fuel factors—smoke-volatility index, smoke point, and NACA *K* factor. The data included in the correlations were obtained over a considerable period of time, and there is some indication that the more recent data (plain symbols, fig. 8(a)) define a correlation curve at a slightly higher level of deposit. The correlations applied equally well to JP-3 and JP-4 fuels.

The relative accuracy of the three fuel-factor correlations can be judged by examining deviations of the deposit data from the correlation curve. The deviations for condition A are as follows:

Fuel factor	Average deviation, %	Maximum deviation, %
Smoke-volatility index	27	95
Smoke point	17	67
NACA <i>K</i> factor	12	30



(a) Organo-metallic and commercial compounds.



(b) Oxygenated compounds. Base fuel, 53-193.

FIGURE 12.—Effect of additive concentration on carbon deposit in single J33 combustor.

The average deviations were calculated from the equation

$$\text{Average deviation} = \frac{\sum \frac{y - y_c}{y_c}}{n} \times 100$$

where $y - y_c$ is the absolute difference between the determined and predicted values of carbon deposit, y_c is the predicted value, and n is the number of determinations.

Data for fuels suspected of being contaminated were not included in these calculations. Based on average deviation or maximum deviation, both the smoke point and the K factor gave more accurate deposit correlations than the smoke-volatility index; the smallest deviations were obtained with the K factor. Smoke point and K factor were also the most accurate of about ten factors examined in reference 1. It should be pointed out that simplicity, as well as accuracy, is an important criterion for a satisfactory fuel procurement specification. The determination of an accurate value of hydrogen-carbon ratio, required to compute the K factor, is considerably more difficult than the measurement of smoke point.

The range of fuel properties included in the correlations of figure 8(a) is much greater than that normally considered for jet-engine fuels. For example, fuel 54-41 had accelerated and existent gum contents about 6 times those allowed by current procurement specifications. This particular fuel produced the high values of maximum deviation noted in the smoke-point and smoke-volatility-index correlations. Data of reference 10 show that high values of gum content can cause increased deposits that may not be predicted by empirical fuel factors. Restricting the range of fuel properties, in order to maintain other desirable fuel characteristics, would be expected to reduce deviations considerably.

At a higher inlet air temperature and pressure simulating an engine with a compressor pressure ratio of 7 operating at sea level (condition B), deposits did not satisfactorily correlate with any of the fuel factors. Preliminary examination of other fuel characteristics that could affect carbon deposition (ref. 1) did not yield any better correlation of the data. The mean straight lines drawn through the data in figure 8(b) are, however, approximately parallel to the corresponding correlation lines for condition A (fig. 8(a)). In reference 11 deposit data obtained at several different operating conditions in an annular combustor also gave approximately parallel correlation lines with K factor. The poor correlation obtained with the condition B data may be the result of more erratic carbon-deposition patterns that were observed at high inlet air temperature. At this condition carbon was deposited in isolated areas around the upstream end of the combustion chamber, and some of the heavier deposits may have broken away from the walls. In comparison, at low inlet air temperature conditions carbon was generally found uniformly deposited in a sizable area around the fuel nozzle of this combustor.

The full-scale-engine data obtained in this investigation are too limited to ascertain the applicability of the correlations to full-scale engines. Additional unpublished carbon-deposit data for three full-scale engines are presented in table

VIII. Two of the engines (types I and III) were of the same type as used in the present investigation. Engine IV had an axial-flow compressor of 6.8 pressure ratio and an annular prevaporizing combustor. The engines were operated 10 hours at static sea-level conditions on cyclic operating schedules. The deposits listed are average values for each combustion chamber of engine types I and III or each vaporizer tube of the annular vaporizing combustor (type IV). Comparison of the data of tables VIII and IV shows that deposit deviations in the full-scale engines are considerably greater than those in the single combustor.

TABLE VIII.—FULL-SCALE-ENGINE CARBON DEPOSITS

NACA fuel	Average carbon deposit, g (a)	Average variation, percent (b)
Engine I		
54-108	45.9	16
54-109	45.3	12
54-110	39.0	11
54-111	43.0	15
Engine III		
54-108	10.4	74
54-109	3.2	74
54-110	1.9	65
54-111	6.0	33
Engine IV		
54-108	2.28	18
54-109	2.15	28
54-110	1.67	26
54-111	1.69	32

a. Arithmetical average deposits in each combustor or fuel vaporizer.

b. Arithmetical average percent variation of deposits in individual combustion chambers, or fuel vaporizers, from arithmetical average deposit values.

The carbon-deposit data obtained with three fuels in the type I full-scale engine at the NACA Lewis laboratory (table V(a)) and the full-scale-engine data of table VIII are plotted against smoke-volatility index, smoke point, and NACA K factor in figure 13. Data for the two type I engines would not be expected to fall on a single curve, since different operating conditions were used. The three fuel factors correlated the limited full-scale-engine (types I, III, and IV) deposit data with about equal accuracy. Percentage deviations for the full-scale-engine correlations were not computed because of the limited number of fuels tested. Carbon deposition in the full-scale engines was affected to a varying degree by changes in fuel properties. For example, deposits in engine IV increased only about 46 percent and those in engine III about 450 percent when the smoke-volatility index was decreased from 56 to 44.

Although less quantitative in nature, the results obtained in full-scale engines II and III tested at the NACA Lewis laboratory exhibited similar trends. In engine II (table V(b)), much more soot was observed in the exhaust muffler with fuel 50-264 ($SVI=45.5$, smoke point=17.2, $K=331$) than with a number of production batches of JP-3 having

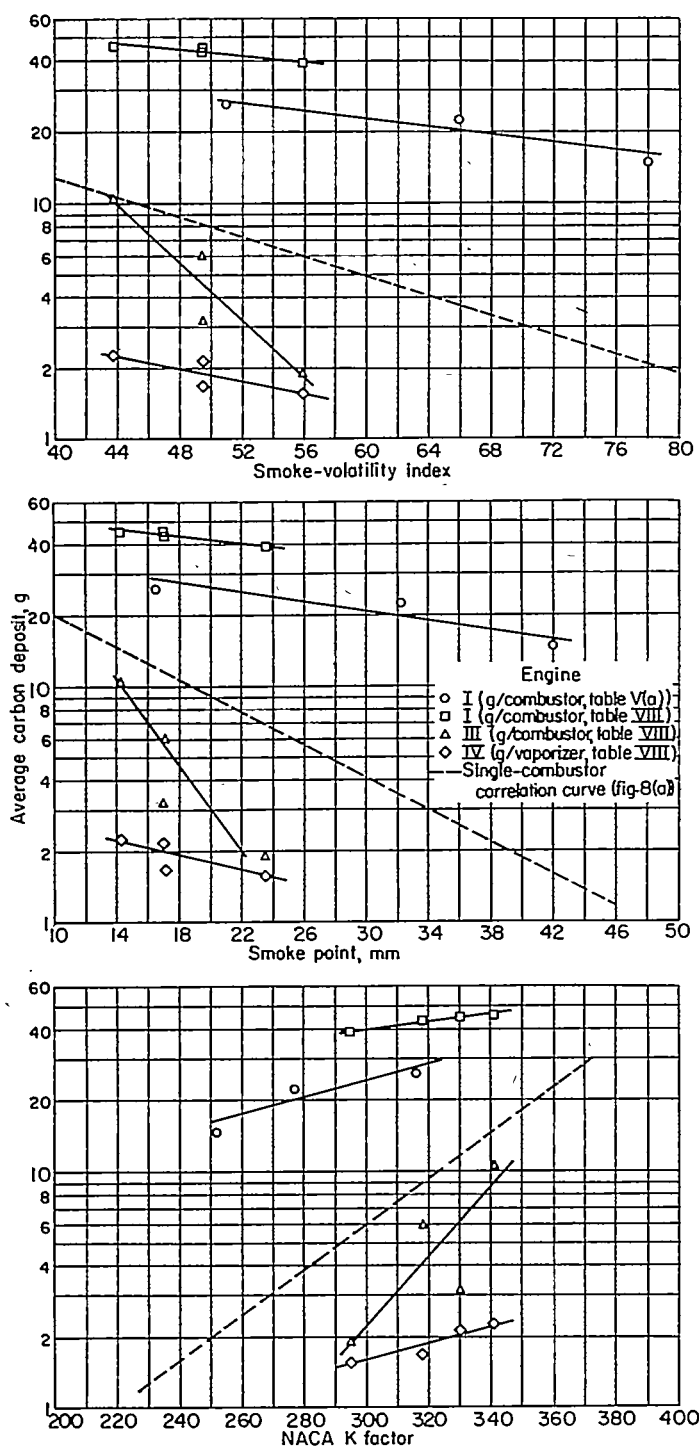


FIGURE 13.—Relation between carbon deposits in full-scale turbojet engines and empirical fuel factors.

properties very similar to those of fuel 52-30 ($SVI=66$, smoke point=32.3, $K=277$). In the type III full-scale engine (table V(c)) much more soot was observed in the exhaust muffler, along with a greater tendency toward spark-

plug fouling, with fuel 52-76 ($SVI=51$, smoke point=16.5, $K=316$) than with production fuels similar to 52-28 ($SVI=78$, smoke point=40.0, $K=252$).

The order of carbon deposition among the fuels in the single combustor at condition A was the same as in the full-scale engines; however, figure 13 shows that percentage changes in the deposit values between the fuels were not the same. Except for engine III, deposits in the single combustor increased at a more rapid rate as "fuel quality" decreased. The variation in sensitivity between the single combustor and the full-scale engine is at least partly attributable to differences in operating conditions. The full-scale engines were operated on cyclic test schedules, whereas the single combustor was operated at constant test conditions. Also, the combustor inlet and outlet passage configurations were different in the single combustor and in the full-scale engines. At the higher pressure and temperature single-combustor condition B, no relation between single-combustor and full-scale-engine data is apparent. The reasons for this inconsistency are probably related to the erratic deposition in the single combustor at condition B.

Neither the absolute level of deposition nor the relative effects of fuel factors on these deposits should be used to distinguish between good and bad combustor design in the full-scale engines tested. In addition to carbon deposition, a number of other performance requirements (e.g., combustion efficiency and stability, structural durability, and ease of manufacture) enter into final combustor designs for turbojet engines.

The empirical fuel factors examined in this investigation represent the volatility characteristics, the hydrogen-carbon ratio, and the smoke point of the fuel. In reference 1, which summarizes early carbon-deposit research in laboratory combustors, many additional fuel properties were observed to affect deposits. Approximate relations between deposits and fuel properties such as aromatic content, aniline point, and specific gravity are reported. Many of these other properties are, for petroleum fuels, interrelated with distillation characteristics, hydrogen-carbon ratio, or smoke point. For example, aromatic content of a fuel directly influences the hydrogen-carbon ratio. Tests to determine the effects of adding specific single-ring and dicyclic aromatic hydrocarbons to jet-type fuels (fuel blends 51-353, 52-32, 52-50, 52-105, 52-118, 52-119, and 52-120) revealed that the smoke-volatility index, smoke point, and K factor satisfactorily predicted changes in carbon deposition.

Other properties of jet fuels (e.g., sulfur content and gum content) are not related to the fuel factors. The effects of sulfur and gum on deposits were investigated in studies reported in reference 10. Limited data indicated that moderate amounts of gum did not influence deposits; very high gum contents, well above those permitted in current

jet fuels, will cause increased deposits. Although the data were not conclusive, it appeared that one form of sulfur (mercaptan) significantly increased deposits while another form (disulfide) had no effect.

EMPIRICAL RELATIONS BETWEEN EXHAUST-GAS SMOKE AND FUEL PROPERTIES

The measured values of smoke density were generally very low and may be of questionable significance. Nevertheless, they did vary with fuel properties in much the same way as did carbon deposition; that is, smoke formation generally decreased with an increase in smoke-volatility index or smoke-point and with a decrease in K factor. Satisfactory relations were obtained only at condition A. While these results indicate that smoke formation and carbon deposition are affected by the same factors, experience has shown that design features tending to alleviate the carbon-deposition problem frequently aggravate the smoke problem, and vice versa. Also, data presented in reference 12 show that, while fuel volatility affected smoke density in a single combustor, the effects were very different at different operating fuel-air ratios. This might explain the fact that correlations with fuel factors were obtained at one condition and not at another in the present investigation. It should also be pointed out that the empirical fuel factors considered were developed for carbon deposition and not for exhaust-gas smoke.

EFFECT OF ADDITIVES ON CARBON FORMATION

The fuel additives investigated represent a fairly wide variety of organo-metallic compounds, oxygen-bearing compounds, and commercial compounds recommended for use in reciprocating engines and furnaces to reduce carbonaceous deposits and smoke. Spectroscopic analyses of the commercial compounds showed that most of them contained some organo-metallic materials. Most of the additives tested significantly reduced carbon deposits of the base fuel. None of them produced effects on exhaust-gas smoke concentration that could be considered significant in view of the variations in smoke concentrations observed with the base fuel.

Among the additives tested, the oxygenated compounds were generally the least effective in reducing deposits in the single combustor. The most effective oxygenated compound, isooctyl nitrate, reduced base-fuel deposits almost 30 percent in a 1-percent-by-weight blend. Most of the organo-metallic compounds and the commercial additives reduced deposits 50 percent or more. Additives A, B, and J, which reduced base-fuel deposits around 70 percent, were the most effective of the commercial additives. Tests with tetraethyl lead and with lead naphthenate showed smaller but still very significant reductions. The most effective compound tested was dicyclopentadienyliron, known commercially as "Ferrocene." This material reduced deposits in all concentrations tested; the largest reduction was 80

percent, obtained with the highest additive concentration tested (0.05 percent by weight) in a No. 2 furnace oil (fuel 53-193).

The weights of deposits reported include any metallic deposits; therefore, actual reductions in carbon deposits obtained with additives containing organo-metallic compounds may have been somewhat greater than reported. Furthermore, since the density of metallic deposits would be expected to exceed the density of carbon deposits, the volume of deposits may be reduced. The volume, rather than the weight, of deposits probably determines the effects on combustor performance.

The results showed that the relative effectiveness of additives varied when they were used with different base fuels. However, the experimental data do not indicate a relation between the effectiveness of an additive and the carbon-forming propensity of the fuel. Thus, the choice of the best additive for use in jet fuels must result from tests with as many widely different fuels as are obtainable under the existing fuel procurement specifications.

The effectiveness of an additive may also be expected to vary with combustor design, since the environment in which the carbon is formed may vary considerably. For example, in a vaporizing-type combustor carbon forms inside the vaporizing tubes as well as in the flame zone. The deposits have been found to be of different composition, indicating differences in mode of formation. Unpublished data have in fact shown different effects of additives on deposits in the flame zone and in the vaporizing tubes of prevaporizing combustors.

Effectiveness in reducing deposits is not the only factor to be considered in choosing an additive. Other factors include possible effects on fuel- and combustion-system components, ease of handling, solubility in jet fuel, storage and high-temperature stability, availability, and cost. There is no information available to indicate whether the additives would be affected by a water-displacement storage system. Very limited data obtained with fuel 52-105 and the blend of 0.005-percent lead naphthenate in 52-105 indicated that the addition of the lead naphthenate caused small increases in both preformed gum (3 to 6 mg/100 ml) and accelerated gum (10 to 14 mg/100 ml). These data indicate the need to investigate this factor.

Limited field experience has indicated marked corrosion difficulties in the exhaust section of turbojet engines operating with fuels containing tetraethyl lead, such as high-octane aviation gasoline. Effects of other metallic additives, such as the dicyclopentadienyliron, on engine operation have not been examined.

All the additives tested are relatively easy to handle and sufficiently soluble in jet fuel, but the relative availability and cost of the additives are unknown.

SUMMARY OF RESULTS

An investigation of the effects of fuel properties and fuel additives on carbon deposition of JP-3 and JP-4 type fuels in turbojet-engine combustors gave the following results:

1. At operating conditions simulating an engine with a compressor pressure ratio of 4 at a 20,000-foot altitude and zero flight speed, carbon deposits and exhaust-gas smoke density correlated with three empirical fuel factors: smoke-volatility index, smoke point, and NACA *K* factor. More accurate correlations of deposits were obtained with smoke point and NACA *K* factor.

2. Single-combustor deposit data at the preceding conditions also correlated reasonably well with limited full-scale-engine deposit data. Deposition in different engines and in the single combustor was not, however, equally sensitive to changes in fuel properties.

3. At higher pressure and temperature operating conditions simulating an engine with a compressor pressure ratio of 7 at sea level and Mach 0.87, neither deposits nor smoke density satisfactorily correlated with any of the fuel factors considered. Also, the deposit data obtained at these conditions did not correlate with full-scale-engine data.

4. A number of fuel additives, including organo-metallic compounds, commercial additives, and oxygenated compounds, significantly reduced combustion-chamber carbon deposits. The most effective additives were those containing organo-metallic compounds, particularly lead and iron compounds. The most effective additive, dicyclopentadienyliron, reduced deposits of the base fuel by approximately 80 percent.

5. Limited tests showed that the relative effectiveness of the additives may vary markedly with properties of the base fuel.

6. None of the additives tested produced significant effects on the exhaust-gas smoke concentration.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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